

Durham Research Online

Deposited in DRO:

17 May 2019

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Peace, A.L. and Phethean, J.J.J. and Franke, D. and Foulger, G.R. and Schiffer, C. and Welford, J.K. and McHone, G. and Rocchi, S. and Schnabel, M. and Doré, A.G. (2019) 'A review of Pangaea dispersal and Large Igneous Provinces – in search of a causative mechanism.', *Earth-science reviews.*, 196 . p. 102865.

Further information on publisher's website:

<https://doi.org/10.1016/j.earscirev.2019.05.009>

Publisher's copyright statement:

© 2019 This manuscript version is made available under the CC-BY-NC-ND 4.0 license
<http://creativecommons.org/licenses/by-nc-nd/4.0/>

Additional information:

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

Accepted Manuscript

A review of Pangaea dispersal and Large Igneous Provinces – In search of a causative mechanism

A.L. Peace, J.J.J. Phethean, D. Franke, G.R. Foulger, C. Schiffer, J.K. Welford, G. McHone, S. Rocchi, M. Schnabel, A.G. Doré



PII: S0012-8252(18)30627-5
DOI: <https://doi.org/10.1016/j.earscirev.2019.05.009>
Reference: EARTH 2865
To appear in: *Earth-Science Reviews*
Received date: 30 November 2018
Revised date: 15 March 2019
Accepted date: 7 May 2019

Please cite this article as: A.L. Peace, J.J.J. Phethean, D. Franke, et al., A review of Pangaea dispersal and Large Igneous Provinces – In search of a causative mechanism, Earth-Science Reviews, <https://doi.org/10.1016/j.earscirev.2019.05.009>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

A review of Pangaea dispersal and Large Igneous Provinces – in search of a causative mechanism

Peace, A. L.¹, Phethean, J.J.J.^{2,3}, Franke, D.⁴, Foulger, G. R.², Schiffer, C.^{2,5}, Welford, J. K.¹, McHone, G.⁶, Rocchi, S.⁷, Schnabel, M.⁴ & Doré, A. G.⁸

1. Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland, Canada

2. School of Environmental Sciences, University of Derby, Kedleston Road, Derby, UK

3. Department of Earth Sciences, Durham University, Durham, UK

4. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany

5. Department of Earth Sciences, Uppsala University, 752 36 Uppsala, Sweden

6. 9 Dexters Lane, Grand Manan, New Brunswick E5G3A6, Canada

7. Dipartimento di Scienze della Terra, Università di Pisa, Pisa, Italy

8. Equinor (UK) Ltd., One Kingdom Street, London W2 6BD, UK

Abstract

The breakup of Pangaea was accompanied by extensive, episodic, magmatic activity. Several Large Igneous Provinces (LIPs) formed, such as the Central Atlantic Magmatic Province (CAMP) and the North Atlantic Igneous Province (NAIP). Here, we review the chronology of Pangaea breakup and related large-scale magmatism. We review the Triassic formation of the Central Atlantic Ocean, the breakup between East and West Gondwana in the Middle Jurassic, the Early Cretaceous opening of the South Atlantic, the Cretaceous separation of India from Antarctica, and finally the formation of the North Atlantic in the Mesozoic-Cenozoic. We demonstrate that throughout the dispersal of Pangaea, major volcanism typically occurs distal from the locus of rift initiation and initial oceanic crust accretion. There is no location where extension propagates away from a newly formed LIP. Instead, LIPs are coincident with major lithosphere-scale shear movements, aborted rifts and splinters of continental crust rifted far out into the oceanic domain. These observations suggest that a fundamental reappraisal of the causes and consequences of Gondwana-breakup-related LIPs is in order.

1.0 Introduction

Throughout geological time the majority of continental lithosphere has several times been assembled into supercontinents (Rogers, 1996; Stampfli et al., 2013; Frizon De Lamotte et al., 2015; Merdith et al., 2019) (Fig. 1). The processes that initiate the dispersal of these large continental accumulations remain controversial (Santosh et al., 2009; Audet and Bürgmann, 2011; Murphy and Nance, 2013; Nance et al., 2014; Petersen and Schiffer, 2016; Peace et al., 2017a; Petersen et al., 2018; Schiffer et al., 2018; Olierook et al., 2019). The debate primarily revolves around whether continental dispersal is driven by deep-rooted thermal anomalies (Morgan-type mantle plumes) or shallow plate tectonic processes (Storey, 1995; Dalziel et al., 2000; Beutel et al., 2005; Frizon De Lamotte et al., 2015; Pirajno and Santosh, 2015; Yeh and Shellnutt, 2016; Keppie, 2016; Petersen et al., 2018; Heron, 2018).

The concept that plumes from the deep mantle are the main driver of continental rifting was originally proposed by Morgan (1971) who suggested plumes provide “*the motive force for continental drift*” and that “*currents in the asthenosphere spreading radially away from each upwelling will produce stresses on the bottoms of the lithospheric plates which, together with the stresses generated by the plate to plate interactions at rises, faults and trenches, will determine the direction in which each plate moves*”. Despite the fact that continental breakup can often be magma-poor (Whitmarsh et al., 2001; Reston, 2009; Franke, 2013) this hypothesis continues to be commonly invoked as a default to explain continental breakup and plate motions, particularly the case where rifting is accompanied by major magmatism (Richards et al., 1989; White, 1992; Campbell and Kerr, 2007).

Alternative models have nevertheless been proposed. The coincidence between the primary Atlantic “hot spots” and the spreading plate boundary has been pointed out (Julian et al., 2015), as has their persistence in near-ridge localities. Such a causal relationship means that those “hot spots” cannot be stationary relative to the underlying mantle. That observation has inspired a number of models including ones that attribute the excess volcanism to fusibility in the source, brought about by excess volatiles (e.g., Bonath, 1990; Ligi et al., 2005) or enhanced source fertility resulting from recycled near-surface materials (Foulger and Anderson, 2005; Foulger et al., 2005b). In the plume model, the persistence of the excess volcanism on the ridge is attributed to “upside-down drainage”, i.e., lateral flow of hot material from a non-ridge-centred, migrating plume, along the underside of the lithosphere to an eruptive site where the lithosphere is thinnest (Sleep, 1996).

A number of non-ridge-centred “hot spots” have also been proposed to lie in the Atlantic, including at Bermuda, the Canary Islands, the Cape Verde Islands and St. Helena. It remains an unanswered question why, if they are fed by deep-mantle plumes, are their products not also channelled to the spreading ridge. Some of these have been attributed to different plume- and non-plume origins, often based on the geochemistry of their lavas. This may be variable, in particular in the source water contents. Proposed mechanisms include lateral flow from a nearby, branching mantle plume (e.g., the proposed multi-headed Tristan plume), flexure of the edge of the continental shelf resulting in lithosphere rupture (e.g., for the Canary and Cape Verde volcanism), and extraction of melt from the low-velocity zone that is ubiquitous

beneath the lithosphere (e.g., Presnall and Gudfinnsson, 2011). Shear heating resulting from motion of the plates must also contribute heat and induce formation of partial melt in the asthenosphere and can account for the availability of melt away from plate boundaries everywhere (Doglioni et al., 2005).

To date, there has been limited discussion of whether the rifting process in itself can account for the excess volcanism observed (Peace et al., 2017a). This is likely partly because there has been relatively little attention paid to modelling the volumes, and ranges in volume, of melt observed (Petersen et al., 2018). Where this has been done, the results are compelling. Asthenospheric upwelling is an inevitable consequence of lithospheric rifting, regardless of the driving mechanism (Huisman et al., 2001; Merle, 2011). In addition, numerical models that include small-scale upwelling can reproduce LIP-scale volumes of melt (Simon et al., 2009).

However, not all rifted margins contain large amounts of magma and there is a continuous spectrum between ‘magma-rich’ and ‘magma-poor’. This is popularly attributed to the presence or absence of a nearby mantle plume or thermal anomaly, thereby attributing it to variations in temperature of the source. Drawing from the alternative, non-thermal models that have been proposed for on-ridge excess magmatism, an explanation in variations in source fusibility and fertility also presents a feasible explanation (Korenaga and Kelemen, 2000; White et al., 2003; Korenaga, 2004; Petersen and Schiffer, 2016; Peace et al., 2017b).

The great structural diversity of continental rifts testifies to their dependence on not just one but many factors (Şengör and Natal'in, 2001; Merle, 2011). Rifts develop in different tectonic environments, on diverse pre-existing structures (Doré et al., 1997; Petersen and Schiffer, 2016; Schiffer et al., this volume), and under slow- or fast-extending conditions (Lundin et al., 2018). They may evolve to form narrow or wide extending zones (Davison, 1997), be magma-poor or magma-rich (Franke, 2013), and exhibit asymmetric or symmetric extension (Becker et al., 2014; Peace et al., 2016).

In this article we review the spatial and chronological relationships between large-volume magmatism and rifting to synthesise the large volume of material already published on this topic rather than introduce new analyses. We analyse in detail Pangaea's dispersal (Fig. 1) in relation to LIPs and other magmatism to test the predictions of a causal relationship between proposed plumes and continental rifting in the Pangaeian realm. Specifically we test two predictions of the active rifting hypothesis, one chronological and the other kinematic:

1. Large-scale volcanism is generated during or just after lithospheric doming but before rifting and breakup (chronological); and
2. Rifting and breakup initiates at the location of thermal uplift and propagates away from it (kinematics).

2.0 The assembly and dispersal of Pangaea

Pangaea was constructed from multiple lithospheric plates that resulted from the disintegration of the previous supercontinent Rodinia. Before Rodinia broke apart in the Late Proterozoic, between 1000 and 700 Ma (Veevers, 2004), it comprised North America, Baltica, Siberia, Gondwana, and other minor components (Torsvik et al., 1996; Stampfli et al., 2013). The disassembly of Rodinia is poorly understood, as geological evidence has been overprinted by later orogenic cycles (Scotese, 2009; Li et al., 2008; Cawood and Pisarevsky, 2006), while the assembly and disassembly of Pangaea is better understood and captured in detailed palaeogeographic reconstructions (Golonka et al., 1994; Stampfli et al., 2013; Blakey and Wong, 2003; Cocks and Torsvik, 2006; Scotese, 2009) (Fig. 1).

Pangaea's earliest breakup and formation of the first oceanic crust occurred in the Triassic and formed the Central Atlantic Ocean. Subsequently, West Gondwana (Africa and South America) and East Gondwana (Antarctica, Australia, India, Madagascar, and New Zealand) started to separate in the Middle Jurassic. This was followed by the Early Cretaceous separation of Africa from South America during the opening of the South Atlantic, then the Cretaceous separation of India from Antarctica, and finally the successful breakup of Scandinavia and Greenland, and the birth of the North Atlantic in the Cretaceous to Early Cenozoic (Fig. 1). Here, we investigate if volcanism associated with each breakup event occurred before, during, or after rifting. We also review the kinematic evolution of each rift and their initial breakup positions in relation to LIPs throughout the dispersal of Gondwana and Laurasia.

The Carboniferous–Permian assembly of Pangaea was preceded by four major tectonic events:

- 1) Disassembly of the supercontinent Rodinia in the late Proterozoic, when Laurentia, Baltica, and Siberia separated from a number of other continents, opening the Iapetus Ocean and the Tornquist Sea between them. Gondwana formed shortly afterwards, in the Cambrian, by re-assembly of the remaining dispersed continents of India, Australia, Sahara, West Africa and other minor blocks (Li et al., 2008).
- 2) In Ordovician-Devonian times, the Caledonian Orogeny sutured Laurussia (North America, Baltica and Avalonia) which had previously drifted northward from Gondwana forming the Rheic Ocean (Cocks and Torsvik, 2011).
- 3) In the Devonian, peri-Gondwana terranes, rifted from Gondwana, opened the Palaeotethys and accreted to southern Laurasia during the Devonian Variscan Orogeny. Siberia and Kazakhstan docked along the eastern Laurussian margin, during the Uralide Orogeny to form Laurasia. This was followed by Carboniferous-Jurassic collision between Gondwana and Laurasia along the Appalachian fold belt, finally assembling western Pangaea (Stampfli and Borel, 2002; Cocks and Torsvik, 2007).
- 4) Assembly of eastern Pangaea (central and SE Asia) in the late Permian-Jurassic involved the closure of the Palaeotethys and the Mongol–Okhotsk Ocean to accrete peri-Gondwana terranes to Siberia and Kazakhstan in the Late Jurassic (Zorin, 1999;

Kravchinsky et al., 2002; Sengor, 1996; Tomurtogoo et al., 2005). The repeated rifting of peri-Gondwana terranes opened the Neotethys.

The dispersal of Pangaea (Fig. 1) occurred through an extended period of Earth's history and is well-summarised in earlier papers (e.g., Dietz and Holden, 1970; Frizon De Lamotte et al., 2015).

Rifting began in western Pangaea in the Triassic-early Jurassic, coeval with the final phases of the assembly of eastern Pangaea, initiating the disassembly of Pangaea. In the mid-Jurassic, continental breakup and seafloor spreading opened the Central Atlantic-Caribbean (Biari et al., 2017) and the Indian Ocean (Powell et al., 1988), breaking Pangaea apart again between North America, West Gondwana (South America and Africa) and East Gondwana (India, Antarctica, Madagascar and Australia) (Schettino and Scotese, 2005). By the end of the Early Cretaceous, East Gondwana was completely detached from West Gondwana, while India separated from Antarctica and Australia and the Amerasia Basin opened in the Arctic. Rifting leading to seafloor spreading started separating South America and Africa from south to north, finally adjoining with Central Atlantic Ocean spreading in the mid-late Cretaceous. Madagascar began diverging from Africa in the Middle Jurassic (Phethean et al., 2016). This was followed by the Labrador Sea opening in the Late Cretaceous (Roest and Srivastava, 1989; Roest and Srivastava, 1989; Chalmers and Pulvertaft, 2001; Peace et al., 2016; Peace et al., 2018a; Abdelmalak et al., 2018), along with the Gulf of Aden (Courtillot, 1980). Early in the Cenozoic, the Labrador Sea was gradually abandoned in favour of rifting between North America-Greenland and Europe which opened the NE Atlantic in the Palaeocene (Srivastava, 1978; Gaina et al., 2017b). The opening of the North Atlantic represents the dispersal and end of the Laurasian continental amalgamation that formed the northern constituent of the Pangaea supercontinent (Hansen et al., 2009; Gaina et al., 2009; Frizon De Lamotte et al., 2015). At the same time Australia separated from Antarctica and Zealandia (Veevers, 2012; Williams et al., 2019), and the Gakkel Ridge started opening the Eurasia Basin in the Arctic (Thórarinnsson et al., 2015).

3.0 The opening of the Central Atlantic

The Central Atlantic is defined here as the region bounded to the north by the Pico and Gloria fracture zones and to the south by the Fifteen-Twenty and Guinean fracture zones (Fig. 2). This oceanic basin comprises the oldest part of the Atlantic Ocean, with oceanic crust dating back to the Triassic-Jurassic boundary (Biari et al., 2017). As this region contains the earliest breakup and formation of oceanic crust, it is a prime region for understanding the whole Atlantic system, including the North and South Atlantic Oceans. Conversely, this area is difficult to explore due to the many complexities involved in the rifting process (Pindell and Dewey, 1982; Reston, 2009).

The North American-African segment of the Central Atlantic has undergone multiple suturing and breakup events along similar axes over at least two Wilson Cycles, suggesting a major control of inheritance in this region (Wilson, 1966; Pique and Laville, 1996; Thomas, 2018). Furthermore, the continental margins are buried below voluminous salt bodies,

making seismic imaging difficult (e.g., Labails et al., 2010). In addition, dating oceanic crust older than Chron M-25 (~155 Ma) has proven problematic because of the Jurassic magnetic quiet zone (Roeser et al., 2002). Breakup of the Central Atlantic was contemporaneous with significant magmatism, namely the Central Atlantic Magmatic Province (CAMP), one of the most significant LIPs which may correspond to the end-Triassic mass extinction (Marzoli et al., 1999; Verati et al., 2007; Nomade et al., 2007; Panfili et al., 2019).

3.1 Overview of Central Atlantic rifting and breakup

The Central Atlantic Ocean opened after a protracted period of rifting (Biari et al., 2017), which led to the formation of major rift basins on the continental margins (Withjack et al., 2012), and is claimed to have displayed significant asymmetry between the Scotian and the Moroccan margins (Maillard et al., 2006). Several ridge-jumps may have occurred during early opening (e.g., Labails et al., 2010). There is also a significant difference in rifting style between the northern and southern parts (Leleu et al., 2016). Extension began in the northern Central Atlantic in the Anisian (Middle Triassic) and the Carnian (Late Triassic) in the southern Central Atlantic, long-lived passive rifting preceded emplacement of the Central Atlantic Magmatic Province (CAMP) at ~201 Ma (Leleu et al., 2016).

Seafloor spreading is thought to have started around 180–200 Ma, either during the Late Sinemurian (195 Ma) (Sahabi et al., 2004) or the Middle Jurassic (175 Ma) (Klitgord and Schouten, 1986). Labails et al. (2010) suggested that the opening of the Central Atlantic started during late Sinemurian (190 Ma), and that initial spreading (up to 170 Ma) was characterised by extremely slow crustal production (~0.8 cm/y half spreading rate). In addition, Labails et al. (2010) show that at the time of the Blake Spur Magnetic Anomaly (BSMA) (170 Ma), the direction of the relative plate motion between Laurentia and Africa changed from NNW-SSE to NW-SE and the half spreading rate increased to ~1.7 cm/y. Labails et al. (2010) also identified a conjugate magnetic anomaly to the BSMA, which they suggest rules out the possibility of a ridge jump. Labails et al. (2010) further reports a significant spreading asymmetry, producing more oceanic crust on the American plate. In addition to the temporal variation in spreading rates identified by Labails et al. (2010), spreading rates in the northern Central Atlantic are thought to be lower than those of the southern Central Atlantic (Klitgord and Schouten, 1986).

While many existing plate reconstructions show isochronous breakup along the whole margin, a detailed analysis of tectonic structures shows differences in the timing for the American margin (Withjack et al., 1998). In particular, Withjack et al. (1998) showed that the rift-drift transition offshore of the SE USA took place at around 200 Ma, while offshore Canada this transition is dated to around 185 Ma. Le Roy and Piqué (2001) analysed rift structures at the Moroccan margin and found a westward migration of extension during Carnian to Rhaetian (Late Triassic) times. They conclude that oceanic accretion could have already started in the early Lower Jurassic. With the assumption of a half spreading rate of 0.8 cm/y (Labails et al., 2010), an interpolation of magnetic anomalies by Roeser et al. (2002) yielded an age estimate for the initial ocean crust offshore Morocco of 193.5 Ma. By forward modelling of magnetic measurements, Davis et al. (2018) concluded that the formation of

Seaward dipping reflector (SDR) packages most probably has taken place at a relatively low extension rate (< 2 cm/y full-spreading). The width of the SDRs suggests that formation of a complete SDR wedge would have taken at least 6 Myr. Assuming that the emplacement of SDRs started directly after the emplacement of the CAMP LIP, Davis et al. (2018) concluded that the earliest oceanic crust within the Central Atlantic has an age of ~ 195 Ma or younger.

3.2 Rifting and magmatism

The opening of the Central Atlantic was contemporaneous with the production of extensive dykes, sills, and surface flows along the margins and interiors of eastern North America, NE South America, NW Africa, and southwestern Europe (Hodych and Hayatsu, 1980; Papezik and Hodych, 1980; Deckart et al., 2005; Nomade et al., 2007; Kontak, 2008; Bensalah et al., 2011; Shellnutt et al., 2017; Denyszyn et al., 2018). This association of basaltic magmatism with continental rifting and breakup indicates features and mechanics of the mantle during both events. The CAMP is certainly one of the largest and most important LIPs globally recognised (Bryan and Ernst, 2008).

Since the 1970s, similarities between Early Mesozoic basalts on the margins of eastern North America and NW Africa have been recognised (e.g., Weigand and Ragland, 1970; May 1971; Bertrand and Coffrant, 1977). The term “CAMP” was first used by Marzoli et al. (1999), who included dykes and sills in NE South America. The extent of the CAMP is primarily defined in previous work by the location of dykes, with the CAMP boundaries drawn based on their farthest known extent. The petrology of the igneous rocks comprising the CAMP distinguishes them from the older and younger basaltic intrusions in the same regions (e.g., Merle et al., 2013). Swarms of related dykes tend to occur in distinct sets of dozens to hundreds with similar orientations and field characteristics. Sills of the CAMP occur both within Mesozoic basins and also in older crustal rocks in South America and Africa. Large tholeiite sills are also mapped in Brazil and western Africa (Davies et al., 2017; Marzoli et al., 1999), while smaller but still-considerable examples are well known in the eastern USA in the Hartford, Newark, and Deep River Mesozoic basins, though not in the older basement rocks.

Mesozoic basins that preserve CAMP extrusive basalts cover a total area of about 300,000 km² (McHone, 2003). However, dykes and sills of the CAMP that fed the basin basalts also occur across 11,000,000 km² within four continents, centred upon but extending far outside of the initial Pangaeian rift zone (Fig. 2). The breadth of the CAMP exceeds 5,000 km, with several dykes longer than 500 km, sills exceeding 100,000 km³, and lava flows possibly larger than 50,000 km³ (McHone, 1996). If only half of the continental CAMP area was originally covered by 200 m of lava, the total volume of the CAMP and the East Coast Margin Igneous Province (ECMIP; the thick rift-related igneous package interpreted to underlie the North American Central Atlantic margin e.g., Holbrook and Kelemen, 1993) extrusive basalt would exceed 2,400,000 km³ and represent one of the largest subaerial flood basalt ever to erupt on Earth. A very large volume may also remain in the uppermost crust in the form of dykes and sills. In addition, basalts of the ECMIP of North America, which most likely cause the East Coast Magnetic Anomaly (Kelemen and Holbrook, 1995), have a

submarine area of about 60,000 km², with perhaps 1,300,000 km³ of extrusive lavas. However, these basalts have not yet been genetically connected to the continental CAMP and it remains a possibility that their formation was a different event, possibly younger, and possibly associated with the onset of seafloor spreading (Benson, 2003).

Whole-rock analyses of dykes, sills, and lavas of the CAMP tend to fall into three chemical groups, as outlined in McHone (2000) and used by Salters et al. (2003). These groups are characterised based on average values of TiO₂: 0.62 % (low, or LTi), 1.26 % (intermediate, or ITi), and 3.21 % (high, or HTi), and other components such as magnesium, nickel, and various element ratios. All are tholeiites, with the LTi group mostly olivine normative, and ITi and HTi groups mostly quartz normative. As expected, phenocrysts of olivine tend to be abundant in the LTi dykes and sills, while minor interstitial quartz can be found in many of the ITi and HTi dykes, as well as early olivine in the larger intrusions.

There are also distinctions with respect to dyke swarm locations and orientations (Fig. 2). Dykes and sills of LTi basalt are nearly all found in basins and NW-trending dyke swarms in the SE USA, whereas most of the HTi dykes are on the margins of South America and Africa that were adjacent before rifting. They also tend to be in NW-SE trending dykes. LTi and HTi magmas are apparently not represented among the remnants of surface flows within the CAMP. The ITi dykes and sills are joined by large basalt flows preserved in rift basins of eastern North America and NW Africa. In those basin areas, the ITi dykes tend to trend NE-SW, but this group is very widespread and also has N-S dykes and other trends in other areas around the CAMP (Fig. 2).

Several localities in the SE USA show ITi dykes crosscutting LTi sills and dykes (Ragland et al., 1983) that are overall temporally overlapping/coeval (~201 Ma) with only minor variations (<0.5 Ma) (Hames et al., 2000; Blackburn et al., 2013). High-precision dates suggest about 570,000 years between the earliest and latest basin basalts (Olsen et al., 2003), based on basin stratigraphy correlated with Milankovitch climatic cycles. The Triassic-Jurassic boundary occurs above the oldest ITi basalts in eastern North America (Cirilli et al., 2009), but the end-Triassic extinction horizon is still defined a meter or so beneath the oldest basin basalt (Olsen et al., 2003). Older basalts and large sills (Davies et al., 2017) exist in Morocco (Deenen et al., 2010) that precede the end-Triassic mass extinction for which it is now generally recognised that the CAMP is the prime causal candidate (Blackburn et al., 2013). The petrological diversity of CAMP basalts thus suggests considerable mantle-source heterogeneity and lithospheric influence on the magmas (Section 3.5).

3.3 Timing of Rifting and Magmatism

Although CAMP magmatism occurred in extremely intense but relatively brief episodes around 201 Ma, the tectonic activity that led to the breakup of Pangaea was much more prolonged (Frizon De Lamotte et al., 2015; Keppie, 2016). The oldest rift basin sediments around the central Atlantic are early Carnian (Late Triassic), possibly older than 230 Ma (Olsen, 1997). In the SE USA, rifting ended before CAMP magmatism, such that sediments and basalts are spread across wide areas rather than being controlled by subsiding basins

(Schlische et al., 2003). Seismic reflection data suggests that younger Cretaceous strata are deposited directly upon the CAMP lava plains (McBride et al., 1989). In the NE rift basins, thick Early Jurassic sediments overlie basalts (Olsen, 1997), showing that rifting continued for 5 to 10 Myrs or more after the youngest CAMP flows, ceasing by the early Middle Jurassic (Schlische et al., 2003). This diachronous rifting was once thought to correspond to the changes in dyke orientations from south to north in eastern North America, but it is now known that the dyke magmas were roughly coeval.

The actual age of continental separation and production of the new ocean is uncertain and needs further research. It is generally assumed, and supported by seismic interpretation (Kelemen and Holbrook, 1995), that eruption of the thick seaward-dipping volcanic wedge along the eastern continental margin of North America immediately preceded the formation of Atlantic Ocean crust. However, the oldest drift sediments along the western Atlantic margin appear to be 179 to 190 Ma (Benson, 2003), or about the age of the youngest post-CAMP rift basin strata. There may thus be a 10-Myr gap between cessation of CAMP magmatism and seaward-dipping wedge magmatism and formation of new ocean crust.

3.4 Kinematics of the Central Atlantic rift – implications for breakup

Early Mesozoic dykes in eastern North America and NW Africa have been proposed to radiate from a central area at the Blake Plateau, near the modern-day Bahamas (May, 1971). This led to a model in which a deeply rooted thermal anomaly produced not only the dykes and basalts (Morgan, 1983) but also caused the rifting of Pangaea and the opening of the Central Atlantic Ocean (Storey et al., 2001). This model has been challenged by numerous previous workers (e.g., McHone, 2000).

McHone (2000) argued that the circum-Atlantic dykes are oriented parallel to segments of adjacent central Atlantic rifted margins (Fig. 2), and are not radial even within sets of regional dykes such as in the SE USA. Moreover, volcanic seamounts and islands of the Atlantic are much younger than breakup, so there is no volcanic plume track from the proposed centre evident, as would be required for such a mechanism (Pe-Piper et al., 1992; Pe-Piper et al., 2013). As described above, rifting that eventually opened the Central Atlantic started > 30 Myr before the magmatism, and the rift basins continued to develop for about another 10 Myr before tectonic activity shifted to the new ocean margins (Olsen, 1997). Thus, rifting was not contemporaneous with the massive production of CAMP basalts as expected for triggering by the arrival of a plume head.

Weigand and Ragland (1970) ascribed the chemical variations of the CAMP basalts to crystal fractionation within lithospheric magma chambers. However, it does not appear that all of the chemical variations observed in the CAMP magmas can be derived through differentiation or contamination of a common mantle melt (Salters et al., 2003). The upper mantle has substantial mineralogical, chemical, and temperature variations, or heterogeneous zones, which also influence composition (Shellnutt et al., 2017). The petrological diversity does not, however, support a model of a narrow mantle plume source (Tollo and Gottfried, 1989).

Components from crustal rocks that were subducted in much older plate collision events characterise most CAMP basalts (Merle et al., 2013; Puffer, 2001; Pegram, 1990). CAMP magmas are clearly derived from different compositions of sub-lithospheric mantle, some with substantial subduction contamination, in specific regions and across large geographic areas unrelated to any single centre. A preferred model for producing the CAMP is by the tectonic release of mantle melts that formed in a mantle warmed as a result of thermal insulation beneath the vast Pangaeon supercontinent (Anderson, 1994; Merle et al. 2013). However, results of numerical models suggest that continental insulation is not the primary influence of supercontinents on mantle temperature (Heron and Lowman, 2010; 2014).

4.0 The breakup of East and West Gondwana

Breakup of East and West Gondwana during Early Jurassic times marked the end of the Gondwana supercontinent (Veevers, 2004; Klimke and Franke, 2016; Phethean et al., 2016) (Fig. 3). Along the central region of the Gondwana rift, two oceanic basins record the tectono-magmatic history of the breakup. These are the West Somali Basin, from southern Somalia to northern Mozambique, and further south the Mozambique Basin, which is conjugate to the Riiser Larsen Sea/Lazarev Sea, Antarctica. Breakup followed a prolonged phase of episodic activity along the Karoo rift system and was closely contemporaneous with the eruption of the Karoo-Ferrar flood basalts and formation of the Lebombo volcanic monocline in Mozambique. Here, we discuss the spatio-temporal significance of tectonic and magmatic events, and their possible influence on breakup.

4.1 Overview East and West Gondwana rifting and breakup

Prior to the Middle Jurassic breakup of East and West Gondwana, tectonic activity along the Southern Trans-Africa Shear System, and much of the future line of continental separation in East Africa, had been underway since the Early Permian (Macgregor, 2018). Rifting associated with this early tectonism led to deposition of Karoo sediments along NW-SE and NE-SW trending basins during three main phases:

- 1) Extension between ~300 Ma and ~265 Ma along NW-SE trending basins and sinistral strike-slip along NE-SW trending basins resulted in sedimentation of rifts and local deposition within left-lateral step-over basins, respectively (e.g., Hankel, 1994).
- 2) A reconfiguration of the rift system occurred between ~259 and ~264 Ma with the onset of extension and rapid subsidence in NE-SW trending basins (Schandelmeier et al., 2004). Strike-slip deformation occurred along formerly extensional NW-SE trending basins (Delvaux, 2001).
- 3) Following the final episode, a brief pause in rifting occurred across most basins between ~249 to ~242 Ma (e.g., Hankel, 1994; Geiger et al., 2004; Frizon De Lamotte et al., 2015). This was followed by rejuvenation of rifting along NE-SW trending rifts (Schandelmeier et al., 2004), and little activity along NW-SE trending rifts (Delvaux, 2001). This rifting episode lasted until ~209 Ma (e.g., Hankel, 1994).

Deposition of Karoo supergroup sediments during these rifting phases was contemporaneous with development of the Cape Fold Belt in South Africa between 220 and 290 Ma (Frimmel et al., 2001). A link has been suggested between episodic development of the Karoo rift system (e.g., Hankel, 1994; Schandelmeier et al., 2004; Reeves et al., 2016) and compression across the Cape Fold Belt (Delvaux, 2001) which reactivated pre-existing basement weaknesses along the northern parts of the Karoo rift system (Reeves, 2014).

A long period of inactivity along the rift system then followed from ~209 Ma to ~183 Ma, after which many branches of the Karoo rift system along the line of future Gondwana separation reactivated in the Early Jurassic (~183 Ma) (Hankel, 1994; Papini and Benvenuti, 2008; Frizon De Lamotte et al., 2015). North of southern Tanzania, and south of northern Mozambique, Jurassic rifting overprints earlier Karoo rifts (Hunegnaw et al., 2007; Kassim et al., 2002; Catuneanu et al., 2005; Macgregor, 2018). The line of Jurassic continental breakup from southern Tanzania through northern Mozambique, however, shows little evidence of following an earlier Karoo rift system (e.g., Macgregor, 2018) and displays very different configurations (Frizon De Lamotte et al., 2015). The distinct Jurassic rifting episode is clearly seen in southwestern Madagascar and southeast Tanzania (Geiger et al., 2004), where new half-grabens developed that crosscut Karoo rift structures and are filled by divergent wedges of Toarcian (Early Jurassic) syn-rift marine shales (Balduzzi et al., 1992; Macgregor, 2018).

4.2 Rifting and magmatism

The Jurassic rifting episode led to the final breakup of East and West Gondwana and was contemporaneous with major magmatism (Fig. 3). The Karoo LIP is primarily composed of the triple junction forming the Lebombo Monocline, the Okavango Dyke Swarm, and the Save-Limpopo Dyke Swarm centred on Mwenezi, Mozambique (e.g., Hastie et al., 2014). Other dyke swarms, sills, and significant flood basalts are preserved in Botswana and South Africa (Jourdan et al., 2005). The inner Explora Wedge and Ferrar LIP (ca. 183.6 ± 1 Ma; Encarnación et al., 1996) forms the Antarctic counterpart of the Karoo LIP.

The Lebombo Monocline may form part of the volcanic rifted margin of Mozambique and continental breakup is thought to have occurred along it (Klausen, 2009; Gaina et al., 2013). The monocline comprises progressively rotated dykes and seaward dipping lava flows, which are laterally segmented by scissor faults. This structure shows similarities to the North Atlantic volcanic rifted margins, and field relationships suggest that early tectonic extension became rapidly overwhelmed by dyke dialation (Klausen, 2009). As such, the Lebombo and Mwenezi volcanics may be the equivalent of SDR sequences (e.g., Davison and Steel, 2018), although the final location of continental breakup is still currently unresolved (e.g. Klausen, 2009).

To the east of the monocline, the Mozambique Plain is underlain by Mesozoic volcanics and basalts have been drilled in the Domo-1 well 300 km east of the Lebombo Monocline (e.g., Davison and Steel, 2018). However, it is uncertain if continental crust underlies these lavas. The final line of breakup may therefore have passed through Mwenezi, or failed here and instead passed around the Mozambique Plain. The Lebombo Monocline was formed over a

long period of ~10 Ma (e.g., Jourdan et al., 2007; Hastie et al., 2014; Riley and Knight, 2001) from ~184 Ma to 174 Ma, with peak activity between 183-178 Ma (Hastie et al., 2014). This is ~3 Myrs earlier than the counterpart Ferrar magmatism on the conjugate Antarctica margin (Riley and Knight, 2001).

Lateral magma flow within the Lebombo Monocline and Okavango Dyke swarm is consistent with a magma source at the nearby Mwenezi triple junction (Hastie et al., 2014). However, the significant magmatism away from the Mwenezi triple junction, which additionally shows magma flow directions inconsistent with a Mwenezi origin, suggest additional sources of magmatism away from the triple junction (Hastie et al., 2014). The triple junction's NE branch, the 070° trending Save-Limpopo dyke swarm, was under orthogonal NNW-SSE extension during its intrusion (Le Gall et al., 2005). In addition, it has been demonstrated that the NW branch, the 110° trending Okavango Dyke Swarm, opened with transtensional dyke intrusion and was also under the same NNW-SSE stress field. Thus, the triple junction structure did not result from active extensional forces radiating from Mwenezi (Le Gall et al., 2005). The magmatism instead followed pre-existing lithospheric structures, in this case alongside an ESE-trending Proterozoic dyke swarm.

Approximately 10% of dykes in the Okavango swarm are Proterozoic, whilst the remaining 90% are Jurassic. Dykes of both ages show a strong geochemical affinity to each other, leading Jourdan et al. (2009) to suggest that both magmatic episodes were sourced from an enriched shallow mantle lithospheric source. Variations in magma composition in the Karoo LIP between low- and high-Ti magmas correlate with Proterozoic and Archean basement (Hawkesworth et al., 1999). Luttinen (2018) proposed an alternative bilateral division of magmas, into subduction and plume-related geochemical affinities, based on relative Nb abundance. There is no evidence for concurrent uplift during magma emplacement (Watkeys, 2002), and magmas young progressively from south to north (Jourdan et al., 2005), i.e. towards the Mwenezi triple junction.

Breakup-related volcanics at the continental margins of the Mozambique Basin, and its conjugates, the Lazarev Sea and the Riiser-Larsen Sea in Antarctica, comprise SDRs and high-velocity lower crustal bodies (Hinz et al., 2004; Leinweber and Jokat, 2012; Mahanjane, 2012; Mueller and Jokat, 2017). However, the volcanics terminate before the Mozambique Strait between Madagascar and Mozambique (Klimke et al., 2018). In the West Somali Basin to the north, there is little evidence for magmatism during the breakup and the basin is thought to be magma-poor (Coffin et al., 1986; Klimke and Franke, 2016; Phethean et al., 2016; Stanton et al., 2016; Stanca et al., 2016).

Despite the many plate kinematic models of breakup of Gondwana along the East African margin (Rabinowitz et al., 1983; Cox, 1992; Reeves et al., 2004; Eagles and König, 2008; Leinweber and Jokat, 2012; Gaina et al., 2013; Nguyen et al., 2016; Phethean et al., 2016; Davis et al., 2016; Reeves et al., 2016), the exact ages of formation of the West Somali and Mozambique basins are still poorly constrained. This is mainly because, if present, the earliest oceanic crust formed during the Jurassic Magnetic Quiet zone, where rapid polarity

changes in the Earth's magnetic field resulted in seafloor spreading anomalies that are difficult to detect (Tominaga et al., 2008). The extinct spreading axis has been tentatively identified using gravity data from the West Somali Basin (Sauter et al., 2016; Davis et al., 2016; Phethean et al., 2016) but the identification of seafloor-spreading-related magnetic anomalies are still an active area of research.

In the West Somali Basin, Davis et al. (2016) identified magnetic anomalies as old as M24Bn (152.43 Ma). Gaina et al. (2013) suggest magnetic anomaly M40ny/M41 (~166 Ma) is the oldest and M2 (~127 Ma) is the youngest magnetic anomaly in the West Somali Basin, extending shorter periods suggested by Rabinowitz et al. (1983) (M10-M25; ~155 Ma to 134 Ma) and Segoufin and Patriat (1980) (M0-M21; ~147 Ma to 124 Ma). In addition, the stratigraphic record from the basin shows an overwhelming to marine sedimentation in the Early Bajocian at around 170 Ma (Coffin and Rabinowitz, 1992), in agreement with a breakup unconformity in the Morondava Basin at this time (Geiger et al., 2004).

Using new geophysical data Mueller and Jokat (2017) and Leinweber and Jokat (2012) tentatively identify M38n.2n or M41n (~164 or 165 Ma) as the oldest magnetic anomaly in the Mozambique Basin, extending earlier-identified seafloor-spreading anomalies M2 to M22 (~148-127 Ma; Segoufin, 1978; Simpson et al., 1979). However, in the conjugate Riiser-Larsen Sea, the oldest magnetic anomaly identified so far is M25n (~154 Ma) (Leitchenkov et al., 2008; Leinweber and Jokat, 2012). The Rooi Rand dyke swarm of the southern Lebombo Monocline has E-MORB geochemical affinity, has been dated at ~173 Ma (Jourdan et al., 2007a; Hastie et al., 2014). It is thought to reflect incipient breakup and early seafloor spreading in the southern Mozambique Basin. These records suggest that breakup in the Mozambique Basin occurred between ~173 Ma and 164.1 Ma, similar to the proposed age of breakup in the West Somali Basin of ~170-152 Ma (references in previous paragraph).

4.3 Timing of rifting and magmatism

The Karoo LIP erupted in Botswana and South Africa from 185 Ma to 178 Ma (Jourdan et al., 2005). Magmatic ages within the Lebombo Monocline, and the Okavango and Save-Limpopo Dyke Swarms overlap each other significantly and lie in the range 183 Ma to 174 Ma (Hastie et al., 2014). If the onshore Lebombo Monocline is in fact a volcanic rifted margin, this would indicate a significant overlap in flood basalt generation and incipient lithospheric breakup of the Mozambique Basin. In view of the south-to-north age progression of the Karoo flood basalts and sills in Botswana and South Africa it is appropriate to compare magmatic ages from the flood basalts and volcanic margins from similar latitudes. Both the Northern Flood Basalt Province described by Jourdan et al. (2005) and the Northern Lebombo Dyke Swarm lie at approximately the same latitude, and were intruded between 182 Ma and 178 Ma (Hastie et al., 2014). Advanced lithospheric extension along the volcanic rifted margin near the Northern Lebombo Dyke Swarm may therefore have already been already present at the time of latitudinally equivalent flood basalt eruption. If, however, the Lebombo Monocline is not the volcanic rifted continental margin, then it is apparent that the LIP volcanism has no spatial relationship with continental breakup that occurred about 200 km farther east.

4.4 Kinematics of the East and West Gondwana breakup – implications for breakup

While earlier studies proposed that the Mozambique Basin and West Somali Basin opened in a generally N-S direction, more recent plate tectonic reconstructions argue for an almost simultaneous opening of both basins in a NW-SE direction (e.g., Gaina et al., 2013; Klimke and Franke, 2016; Phethean et al., 2016; Reeves et al., 2016). This is supported by the stress configuration derived from dyke swarms of the Karoo LIP emplaced during the Jurassic rift phase (Le Gall et al., 2005). Several dyke swarms record a NNW-SSE initial opening direction during the Jurassic (Le Gall et al., 2005).

NNW-SSE gravity lineaments related to spreading in proximity to the African coast have been identified within the Western Somali Basin, between Madagascar and Africa (Davis et al., 2016; Phethean et al., 2016). This newly identified phase of NNW-SSE spreading lasted between ~170 Ma and ~153 Ma and is consistent with the initial NNW-SSE opening of the Mozambique Basin (Phethean et al., 2016). NNW-SSE spreading was superseded by N-S spreading from ~153 Ma following the passing of Madagascar beyond the continental lithosphere of Mozambique and development of the Davie Fracture Zone (Reeves, 2017) along which East Gondwana was transposed.

Reeves et al. (2016) performed plate tectonic reconstruction and found initial NW-SE motion is required. The pole of rotation between East and West Gondwana during the early phase of separation (~183 Ma to ~153 Ma) lay ~2000 km west of the SW tip of present-day Africa. This pole location requires that extension rates across the Gondwana rift increase to the NE. As the time of breakup is primarily a function of cumulative extension across a rift, this would result in SW-propagating breakup between East and West Gondwana. Such a structural configuration is generally supported by the sedimentological record (Salman and Abdula, 1995) and would indicate that the rift propagated towards the Mwenezi triple junction.

Understanding of the timing and kinematics of the Western Somali Basin, and to the south of this the Mozambique Basin and its conjugate the Riiser Larsen Sea/Lazarev Sea, Antarctica, is still incomplete. As a result it is difficult to derive a final and conclusive model about the relationship between the Jurassic breakup of East and West Gondwana, including the formation of the Mwenezi triple junction and the Karoo-Ferrar LIP. However, it is clear that the triple junction structure was not the result of active extensional forces radiating from Mwenezi, and magmatism instead followed pre-existing lithospheric structures. The massive magmatic extrusion that formed the Karoo-Ferrar LIP likely predates rifting but breakup and formation of the oceanic basins did not initiate close to the triple junction. It is therefore more likely that the rift and subsequent breakup migrated towards the triple junction. Nevertheless, work is still needed to fully understand the relationship between the Jurassic breakup of East and West Gondwana and the formation of the Mwenezi triple junction and the Karoo-Ferrar LIP.

5.0 The opening of the South Atlantic

In the Early Cretaceous, West Gondwana, a southern constituent of Pangaea, broke up to form South America and Africa with continuous spreading resulting in the sustained expansion of the South Atlantic Ocean (Rabinowitz and Labrecque, 1979; Ben-Avraham et al. (1997) Lawver et al., 1998; Jokat et al., 2003; Eagles 2007; Moulin et al., 2009; Lovecchio et al., 2018) (Fig. 4). The contemporaneous Paraná–Etendeka continental flood-basalt provinces in Brazil and Namibia, respectively, are frequently attributed to an Early Cretaceous Tristan da Cunha plume with the Walvis Ridge and Rio Grande Rise comprising plume tail magmatism (Morgan, 1981; Peate, 1997). As discussed herein, there are significant spatial and temporal mismatches between the proposed plume and these structures.

5.1 Overview of South Atlantic rifting and breakup

Regardless of the remarkable geometrical fit between the rifted continental margins of South America and Africa (Fig. 4), systematically initially investigated by Wegener (1915) and by numerous workers since (e.g., Gladchenko et al., 1997; Granot and Dymant, 2015), both the rift and breakup phases were complex, with evidence of multiple stages of rifting (Lovecchio et al., 2018), and the possible influence of structural inheritance (Ben-Avraham et al., 1997; Salomon et al., 2015).

Continental extension may have begun in isolated centres in South America during the Late Triassic (at about 210 Ma) when almost all parts of south and west Gondwana were affected by magmatism resulting in high heat flow (Macdonald et al., 2003). In addition to this Late Triassic to Early Jurassic rifting phase, there was a Middle Jurassic extensional phase lasting almost 40 Ma, from Valanginian to late Albian time (Early Cretaceous), that completed separation of Africa and South America to separate completely (Keeley and Light, 1993; Szatmari, 2000). The line of continental separation and the position of the principal failed rifts were controlled by the position of boundaries between different aged basement and the inheritance of basement structural grain (Macdonald et al., 2003). Breakup is reasonably well understood but location and magnitude of continental intraplate deformation during rifting, particularly affecting South America, requires further work (see e.g. Eagles, 2007; Heine et al., 2013; Moulin et al., 2009; Torsvik et al., 2009).

5.2 Rifting and magmatism

Continental breakup and initial seafloor spreading in the South Atlantic were accompanied by extensive transient magmatism as inferred from sill intrusions, flood basalt sequences, and voluminous volcanic wedges and high-velocity lower crust at the present continental margins. Voluminous volcanism affected both Mesozoic intracratonic basins onshore (Paraná–Etendeka flood-basalt province; Peate, 1997; Renne et al., 1992; Trumbull et al., 2007; Foulger, 2017) and the rifted crust offshore (Bauer et al., 2000; Franke et al., 2007; Gladchenko et al., 1997; Gladchenko et al., 1998; Hinz et al., 1999; Koopmann et al., 2014; Mohriak et al., 2008; Paton et al., 2016; Stica et al., 2014) (Fig. 4).

Menzies et al. (2002) and Moulin et al. (2009) compiled published geochemical data and radiometric dates for the dykes and the lava flows of the Paraná–Etendeka flood-basalt

provinces. According to these compilations, volcanic activity peaked in the late Hauterivian – early Barremian (Early Cretaceous; 133–129 Ma, and 134–130 Ma, respectively). Apart from the age of the basalts, there is controversy about the source of Paraná–Etendeka magmas (see e.g. Renne et al., 1992; Peate, 1997; Hawkesworth et al., 1999; Trumbull et al., 2007; Rocha-Júnior et al., 2013; Comin-Chiaramonti et al., 2011; Will et al., 2016; Foulger, 2017).

The Early Cretaceous opening of the southern South Atlantic took place between 135 to 126 Ma (Heine et al., 2013; Moulin et al., 2009; Macdonald et al., 2003; Rabinowitz and Labrecque, 1979). Multichannel seismic and potential field data suggest the oldest magnetic chron in the southern South Atlantic related to oceanic spreading is M9 (ca. 135 Ma) Moulin et al., 2009). Older anomalies, previously identified as M11 (ca. 137 Ma), are found within the SDRs (Koopmann et al., 2016; Corner et al., 2002). There is still some uncertainty about the age of the first oceanic crust near the Falkland Plateau, where strike-slip deformation from the Falklands-Agulhas fracture zone hampers identification of the earliest spreading anomalies. Collier et al. (2017) and Hall et al. (2018) identified M10r (134.2 Ma, late Valanginian) as the oldest recognisable chron at the southern tip of the South Atlantic. This agrees with the suggestion of Becker et al. (2012) that the breakup unconformity, identified in rift basins at the northern edge of the Falkland plateau, is contemporaneous with the well-dated rift-to-sag unconformity in the North Falkland Basin. This indicates a Valanginian (~135 Ma; Early Cretaceous) age for the first oceanic crust in the southern South Atlantic.

Most of the southern South Atlantic continental margins are volcanic (Gładczenko et al., 1997; Becker et al., 2014; Foulger, 2017) (Fig. 4). However, the southernmost 400-km-long portion lacks SDRs (Koopmann et al., 2014b; Becker et al., 2012; Franke et al., 2010; Hall et al., 2018). Thus, from the magnetic anomalies seaward of the SDRs, volcanic rifting onset abruptly, shortly before 137 Ma (Koopmann et al., 2016). From there towards the north, the progressive continental breakup was accompanied by large-scale transient magmatism with the formation of voluminous SDR wedges and high-velocity lower crustal bodies over the ~1800 km to the Florianópolis/Rio Grande fracture zones offshore Namibia/Brazil (Becker et al., 2014). The SDRs were emplaced consecutively northward, as indicated by the progressive termination of the pre-M4 magnetic seafloor spreading anomalies within the volcanic wedges. Only from magnetic chron M4 (ca. 130 Ma) onward was oceanic crust formed across the entire southern South Atlantic (Koopmann et al., 2016).

Although magnetic anomalies from M4 (~130 Ma) onwards have been proposed for the central South Atlantic, north of the Florianópolis (or Rio Grande) fracture zone (Bird and Hall, 2016), most authors agree that breakup was delayed (by 10–20 Myr) across this fracture zone (Torsvik et al., 2009; Moulin et al., 2009; Quirk et al., 2013; Heine et al., 2013). At the latitude of the Paraná–Etendeka flood-basalt provinces, rift propagation was apparently blocked. At this position, one of the fundamental structures in the South Atlantic development (Moulin et al., 2013), the Florianópolis (or Rio Grande) fracture zone, is found. This fracture zone hosted significant offset during breakup (150 km; Elliott et al., 2009). To its north, the central South Atlantic is characterised by minor SDRs which were deposited contemporaneously with Aptian salt deposits (Mohriak et al., 2008). A number of aborted

rifts developed along the Brazilian margin (the Campos, Santos, and Espírito Santos Basins) and the crust was extremely stretched and thinned before the two spreading axes in the central and southern South Atlantic connected (Mohriak et al., 2002; Evain et al., 2015).

Sporadic but widespread magmatic activity continued well after breakup (80 Ma and younger) in southern Africa and Brazil (Comin-Chiaromonte et al., 2011). This magmatism is most commonly manifest as alkaline intrusions, which are locally numerous (e.g., kimberlite fields) but smaller in volume than the Early Cretaceous activity.

5.3 Timing of rifting and magmatism

A key question is the relative timing of extension and emplacement of the large-volume magmatic flows, both onshore (Paraná–Etendeka flood-basalts) and offshore (SDRs). The best estimate currently available for the onset of rifting adjacent to the Walvis Ridge/Rio Grande Rise is about 134–135 Ma (Bradley, 2008; Moulin et al., 2009). This preceded surface breakup in the immediate vicinity. In both provinces, the basalts were deposited in north-south-trending rift basins, showing that rifting preceded flood volcanism, however (Clemson et al., 1997; Glen et al., 1997). The Paraná–Etendeka flood-basalts also erupted at the intersection of a major, activated, transverse extensional structure with the developing line of breakup (Foulger, 2017). Numerical modelling suggests that depth-dependent extension was underway for a considerable period before surface rupture. This is in line with the magma flow directions of both the basaltic rocks from the Etendeka igneous province of Namibia and from the Paraná province in Brazil.

Magnetic seafloor spreading anomalies indicate that the peak magmatism (~132 Ma) of the Paraná–Etendeka flood-basalts postdates emplacement of SDRs in the southern South Atlantic (Koopmann et al., 2016). Only if the M-sequence geomagnetic polarity timescale is used (Malinverno et al., 2012), instead of the popular Gradstein and Ogg (2012) timescale, does dating suggest that the SDRs were emplaced simultaneously (Koopmann et al., 2016). As the SDRs mark the final stage of continental rifting it is evident that the complete extensional phase and likely also earliest seafloor spreading in the southern South Atlantic predate the emplacement of the Paraná and Etendeka basalts (Franke, 2013).

5.4 Kinematics of the South Atlantic rift – implications for breakup

The South Atlantic opened by south-to-north propagation (Gaina et al., 2013; Heine et al., 2013; Seton et al., 2012; Moulin et al., 2009; Jokat, 2003; Macdonald et al., 2003; Austin and Uchupi, 1982; Rabinowitz and Labrecque, 1979) (Fig. 4). As pointed out by Franke (2013), this opening direction contradicts the hypothesis that rifting migrated away from the Paraná–Etendeka flood-basalt provinces (Fig. 4). On the contrary, rifting migrated towards it, at odds with a model whereby continental breakup was triggered by an active upwelling mantle plume currently beneath the Tristan da Cunha hotspot. Other candidate mechanisms must therefore be sought as a trigger for breakup.

When reconstructing the South Atlantic, the Cape fold belt in South Africa aligns with the Ventana (or Sierras Australes) Hills in Argentina. Paton et al. (2016) identify the South African Cape fold belt offshore South Africa and propose that initial rifting along western Gondwana was a consequence of extensional reactivation of the western Gondwanan Fold Belt (Fig. 4). The rift basins are thought to have formed through gravitational collapse of the fold belts such that rift basin geometry was controlled by underlying fold belt geometry. This resulted in broadly SW-orientated (with respect to Africa) extension in Argentina/South Africa. According to Paton et al. (2016), during the mid-Cretaceous, the rift configuration changed significantly and extension followed a north–south trend, i.e. perpendicular to the fold-belt. This geometry fits well with the proposed earlier clockwise rotation of extensional deformation throughout the Early Cretaceous based on structural data from the continental margins (Franke, 2013).

The highly asymmetric subequatorial margins of Brazil and West Africa almost certainly did not rift apart in a pure-shear fashion and simple-shear rifting mechanisms have been suggested (Mohriak et al., 2008). In addition, it has been suggested that the structure and shape of the continental margins show considerable deviations from symmetric structures expected from active rifting, triggered by a plume below the rift (Geoffroy, 2005; Campbell and Kerr, 2007). However, if there was a plume, the style and shape of breakup would still be governed or at least influenced by inherited lithospheric structures, so the margins could still have any kind of complexities, including asymmetry. With respect to volcanics, high-velocity lower crust, dyke orientations, and fault patterns, the complementary southern South Atlantic rifted margins experienced distinct asymmetric evolution during breakup (Salomon et al., 2017; Koopmann et al., 2016; Becker et al., 2016; Becker et al., 2014). The asymmetry in offshore magmatism with considerably more SDRs and volume of high-velocity lower crust on the African margin is surprising, given the opposite asymmetry in the onshore Paraná–Etendeka flood-basalt provinces. On the basis of fission-track and denudation studies on both margins, an explanation in greater post-rift uplift and erosion on the African margin has been ruled out (Becker et al., 2014). Instead, South America offered more favourable structures for magma ascent and extrusion than South Africa. This supports mainly passive rifting as proposed earlier by Maslanyj et al. (1992).

A seismic refraction study at the easternmost Walvis Ridge, including the junction with the Namibian coast, found a small intruded area around the Walvis Ridge (Fromm et al., 2015). Also onshore, in the landfall area of the Walvis Ridge at the Namibian coast, a narrow region (<100 km) of high-seismic-velocity anomalies in the middle and lower crust, interpreted as a massive mafic intrusion, has been identified by seismic reflection and refraction data (Ryberg et al., 2015). These data and observations are not particularly consistent with a broad thermal plume head beneath the opening South Atlantic.

To the north of Walvis Ridge, the abrupt disappearance of SDRs (Elliott et al., 2009) accompanies a dramatic decrease in crustal thickness from 35 km below Walvis Ridge to 5–6 km crust in the central South Atlantic (Fromm et al., 2015). A similar sudden disappearance of SDRs occurs south of a major transfer zone in the southern South Atlantic (Koopmann et

al., 2014b; Becker et al., 2012). These abrupt changes in magmatic volume are also inconsistent with a large-scale thermal source in the sublithospheric mantle as an origin for the magmatism. Gradual variations of mantle properties and dynamics are expected to generate smooth transitions over at least a hundred or a few hundreds of kilometres, not sharp transitions (Franke et al., 2010).

In addition, the architecture of the SDRs implies an episodic emplacement with multiple magmatic phases alternating with magma-starved phases (Franke et al., 2010). The South Atlantic unzipped in jumps from south to north and the SDRs were emplaced consecutively along the successive northward propagating rift zones (Clemson et al., 1997; Franke et al., 2007; Koopmann et al., 2014; Stica et al., 2014). Between the Falkland-Agulhas fracture zone and the Walvis Ridge/Rio Grande Rise (Fig. 4), this process lasted for approximately 5 Myrs as shown by the earliest magnetic chrons in the South Atlantic (Koopmann et al., 2016; Hall et al., 2018).

6.0 Opening of the NE Atlantic, the Labrador Sea and Baffin Bay

The northern North Atlantic realm contains two main spreading branches (Vogt and Avery, 1974) (Fig. 5). The Labrador Sea – Baffin Bay system (here referred to as the NW Atlantic as in Abdelmalak et al., 2018) separated Greenland and North America (Vogt and Avery, 1974; Srivastava, 1978; Torsvik et al., 2002; Hosseinpour et al., 2013; Peace et al., 2016; Welford et al., 2018). Subsequently, the NE Atlantic began to open, separating Greenland and Europe (Talwani and Eldholm, 1977; Skogseid et al., 2000; Lundin and Doré, 2005b; Le Breton et al., 2012; Gaina et al., 2009; Gernigon et al., 2015; Gaina et al., 2017a; Gaina et al., 2017b; Schiffer et al., 2018; Foulger et al. this volume). A complex junction exists between these branches to the north of the Charlie-Gibbs Fracture Zone (CGFZ) (Gaina et al., 2009) (Fig. 5). Switchover from the western spreading ridge to the eastern ridge was one of the most significant events in the evolution of the North Atlantic (Nielsen et al., 2007; Jones et al., 2017). Understanding the mechanisms that drove this switchover remains one of the most important unresolved questions in understanding North Atlantic tectonics (Peace et al., 2017a).

In addition to these first-order spreading axes, Northeast Atlantic oceanic crust is further structurally divided in proximity to Iceland by the Kolbeinsey and Aegir ridges (Fig. 5). The genesis of Iceland, and the proximal Jan Mayen Microplate Complex (JMMC) still present unresolved questions (e.g., Müller et al., 2001; Foulger and Anderson, 2005; Gernigon et al., 2015; Blischke et al., 2016; Schiffer et al., 2018b; Blischke et al., 2019; Schiffer et al. this volume). Regions where major extension occurred without breakup (i.e. failed rifts and transforms), must be accounted for in geodynamic models. These include the Davis Strait (Suckro et al., 2013; Peace et al., 2018b), the North Sea (Cowie et al., 2005), the Rockall Basin (Shannon et al., 1994; Roberts et al., 2018), and the Hatton Basin (Hitchen, 2004) and potentially also the Greenland-Iceland-Faeroes Ridge (GIFR) (Foulger et al. this volume). In addition, diffuse intracontinental deformation may also have been associated with breakup (e.g., the Eureka Orogeny; Nielsen et al., 2007; Nielsen et al., 2014; Heron et al., 2015; Piepjohn et al., 2016; Schiffer and Stephenson, 2017; Gion et al., 2017; Stephenson et al. this

volume). Although difficult to quantify, these events must be accounted for in models of the breakup of the North Atlantic (Ady and Whittaker, 2018).

6.1 Overview of North Atlantic rifting and breakup

Prior to breakup, the proto-North Atlantic region comprised an assemblage of Archaean and Proterozoic terranes (Kerr et al., 1996; St-Onge et al., 2009; Štolfova and Shannon, 2009; Engström and Klint, 2014; Grocott and McCaffrey, 2017; Schiffer et al. this volume). Understanding the pre-breakup extensional phases and orogenies is crucial to understanding Mesozoic-Cenozoic breakup because of the clear influence of structural inheritance (Dore et al., 1997; Schiffer et al., 2015; Peace et al., 2018a; Peace et al., 2018b; Schiffer et al., 2018a; Phillips et al., 2018; Rotevatn et al., 2018; Gernigon et al., 2018; Schiffer et al. this volume).

Following the collision of Laurentia, Baltica and Avalonia in the Ordovician and Silurian (Roberts, 2003; Gee et al., 2008; Leslie et al., 2008), and subsequent gravitational extensional collapse (Dewey, 1988; Dunlap and Fossen, 1998; Rey et al., 2001; Fossen, 2010), the North Atlantic region may have experienced phases of lithospheric delamination and associated uplift for 30–40 Ma followed by a long period of rifting (Andersen et al., 1991; Dewey et al., 1993). The North Atlantic margins, including the Labrador Sea and Baffin Bay, experienced multiple phases of extension between the Devonian collapse of the Caledonian Orogen (Roberts, 2003) and early Cenozoic break-up (Srivastava, 1978; Doré et al., 1999; Lundin and Doré, 2018).

Multiple pre-breakup rift phases are documented in the stratigraphic record of both the NE and NW Atlantic (Umpleby, 1979; McWhae et al., 1980; Srivastava, 1978; Lundin, 2002; Oakey and Chalmers, 2012; Barnett-Moore et al., 2016; Nirrengarten et al., 2018). Rifting started as early as the Permian, was widespread during the Triassic, and continued into the Jurassic Cretaceous, and Cenozoic (Umpleby, 1979; Stoker et al., 2016). In the NE Atlantic, an early rifting pulse from Late Permian to earliest Triassic is expressed regionally in the stratigraphic record. These Permian–Triassic successions record a northward transition from an arid interior setting to a passively subsiding mixed-carbonate siliciclastic shelf margin (Stoker et al., 2016). In the Early Jurassic, the sedimentary record shows thermal subsidence and mild extensional tectonism (Stoker et al., 2016). In the Late Jurassic, the stratigraphic record reveals an intense phase of rifting across most of the NE Atlantic. Cretaceous sections record predominantly marine strata deposition within broad zones of extension (Stoker et al., 2016).

Following prolonged regional rifting (Larsen et al., 2009; Stoker et al., 2016), propagation of the Central Atlantic into the proto-North Atlantic began in Early Aptian time (e.g., Lundin, 2002; Barnett-Moore et al., 2016). The propagating spreading centre produced the oldest oceanic crust of the North Atlantic and is marked by the M0 magnetic anomaly (121–125 Ma; Malinverno et al., 2012) offshore Iberia and Newfoundland (Lundin, 2002; Tucholke et al., 2007; Eddy et al., 2017). By the Late Aptian (Early Cretaceous), spreading reached the Galicia Bank (Boillot and Malod, 1988). This was followed by formation of the Bay of Biscay triple junction in the Late Aptian or Early Albion (Early Cretaceous) where spreading

continued until the Late Cretaceous (Williams, 1975). From the latest Cretaceous to the Eocene, however, the NW movement of Iberia with respect to Eurasia caused the Bay of Biscay to partly subduct beneath Iberia, forming the Pyrenees (Boillot and Malod, 1988). From the Bay of Biscay triple junction spreading propagated NW and reached the Goban Spur in Middle to Late Albian time (e.g., Tate, 1993). By the Santonian (Late Cretaceous), breakup had reached the Charlie Gibbs Fracture Zone (CGFZ) and significant extension, occurred in the Rockall Basin during the Cretaceous (Shannon et al., 1994; Hitchen, 2004).

The NW Atlantic was the next region to open (Srivastava, 1978; Chalmers and Pulvertaft, 2001; Lundin, 2002; Hosseinpour et al., 2013; Keen et al., 2017; Oakey and Chalmers, 2012; Abdelmalak et al., 2018; Welford et al., 2018). This extinct spreading system comprises the Labrador Sea in the south and Baffin Bay in the north (Fig. 5) (Chalmers and Pulvertaft, 2001). These are connected via the Ungava Fault Zone, a transform fault system running through the Davis Strait bathymetric high (Suckro et al., 2013; Peace et al., 2017a; Peace et al., 2018c). The Labrador Sea, Davis Strait and Baffin Bay formed via multiphase, divergent motion between Greenland and North America (e.g., Chalmers and Pulvertaft, 2001; Hosseinpour et al., 2013). Rifting prior to breakup occurred from at least the Early Cretaceous, but potentially as early as the Triassic according to dykes in southwest Greenland (Larsen et al., 2009; Secher et al., 2009) and, with some uncertainty, Labrador (Wilton et al., 2002; Tappe et al., 2006; Tappe et al., 2007; Wilton et al., 2016; Peace et al., 2016).

Onset of spreading in the Labrador Sea is thought to have occurred in the Early Campanian (Chron 33; ca. 80 Ma) (Roest and Srivastava, 1989; Srivastava and Roest 1999). In contrast, Chalmers and Laursen (1995) propose that Chrons 33 and 27 represent transitional crust with true oceanic crust in the Labrador Sea first generated in the Palaeocene (Chron 27; ca. 62 Ma). Keen et al. (2017), however, state that the ocean-continent boundary lies near magnetic anomaly Chron 31 (ca. 68 Ma), and divide the oceanic region into inner and outer domains, which merge near magnetic Chron 27 (ca. 62 Ma). The outer domain of Keen et al. (2017) is interpreted as steady-state seafloor spreading with well-developed linear magnetic anomalies, while the igneous crust of the older, inner domain is generally thinner, and more variable.

During the separation of Greenland and North America, oceanic crust was not formed in the Davis Strait (Suckro et al., 2013; Peace et al., 2017b), in part because of the primarily strike-slip nature (Wilson et al., 2006; Peace et al., 2018c). In Baffin Bay, oceanic spreading probably also occurred simultaneously with spreading in the Labrador Sea. This is, however, uncertain and oceanic crust there is undoubtedly more limited (Jackson et al., 1979; Hosseinpour et al., 2013). Regardless of the existence of older oceanic crust in the Labrador Sea, it is generally accepted that Early Eocene (Chron 24; ca. 54 Ma) oceanic crust floors Baffin Bay (e.g., Chalmers and Pulvertaft, 2001).

Events in the NW Atlantic may be linked to changes in plate kinematics in the NE branch of the Atlantic (Gaina et al., 2009). During the Early Eocene (Chron 24; ca. 54 Ma), seafloor spreading began in the NE Atlantic, marking a major tectonic reorganisation (Lundin, 2002; Nielsen et al., 2007; Mosar et al., 2002; Gaina et al., 2016). The direction of spreading in the Labrador Sea and Baffin Bay system rotated to NNE-SSW (e.g., Abdelmalak et al., 2012;

Peace et al., 2018a). This slowed seafloor spreading that was oblique to the earlier ridge system (Hosseinpour et al., 2013). A triple junction formed between the Labrador Sea, the NE Atlantic, and the southern North Atlantic, which was active until spreading ceased in the Labrador Sea in the earliest Oligocene (Chron 13; ca. 35 Ma) (e.g., Srivastava & Roest 1999). In the NE Atlantic, the abnormal thickness of the oceanic crust initially produced (ca. 54 Ma) decreased and a steady state was reached by the Middle Eocene (ca. 48 Ma) (Holbrook et al., 2001b; Lundin and Doré, 2005b; Storey et al., 2007; Mjelde and Faleide, 2009). By ca. 36-32 Ma, spreading had entirely relocated to the NE Atlantic (Roest and Srivastava, 1989; Barnett-Moore et al., 2016) and terminated along the Labrador Sea-Baffin Bay axis (Chalmers and Pulvertaft, 2001). Greenland then became part of the North American plate (Oakey and Chalmers, 2012; Barnett-Moore et al., 2018).

In the Norwegian Sea of the NE Atlantic, development of sea-floor spreading along the Reykjanes, Mohns, Ægir and Kolbeinsey ridges is relatively well understood (e.g., Lundin, 2002; Gernigon et al., 2015; Blischke et al., 2016; Zastrozhnov et al., 2018). The Ægir Ridge may represent the southern tip of a southward-propagating Arctic rift system that migrated west to form the Kolbeinsey Ridge. This was a transitional process with delocalisation starting at ~40 Ma and the Ægir Ridge becoming extinct sometime between ca. 21 and 28 Ma (e.g., Lundin, 2002). The overlapping geometry of the Ægir and Kolbeinsey Ridges was maintained during the subsequent sea-floor spreading (Müller et al., 2001; Schiffer et al., 2018). The Kolbeinsey Ridge linked with the Mohns Ridge, via the West Jan Mayen Fracture Zone in earliest Oligocene time (Chron 13; ~33 Ma) as indirectly dated by the eastern termination of the West Jan Mayen Fracture Zone, which reaches Chron 13 on the east side of the Mohns Ridge. This link made further spreading along the Ægir Ridge redundant and seafloor spreading ceased along the Ægir Ridge at approximately Chron 12 (Jung and Vogt, 1997). The link between the Kolbeinsey and Mohns ridges represents the linkage between the Arctic and Atlantic oceans (Lundin, 2002).

6.2 Rifting and Magmatism

Rifting and breakup of the northern North Atlantic was accompanied by significant, widespread magmatism (Eldholm and Grue, 1994; Mjelde et al., 2008; Hansen et al., 2009; Nelson et al., 2015; Wilkinson et al., 2016; Á Horni et al., 2017; Clarke and Beutel, this volume) (Fig. 5). This was particularly abundant during and after breakup (Saunders et al., 1997; Hansen et al., 2009; Wilkinson et al., 2016; Á Horni et al., 2017), although some magmatism also occurred during the preceding rifting (e.g., Larsen et al., 2009; Wilkinson et al., 2016). The continental passive margins of the southern North Atlantic (e.g. Newfoundland – Iberia and Labrador – southwest Greenland) are typically considered to be magma-poor (Chalmers, 1997; Chonian et al., 1995; Chalmers and Pulvertaft, 2001; Whitmarsh et al., 2001; Keen et al., 2017), whereas the margins further north (e.g., East Greenland, the NW European margin, and Central West Greenland) are considered to be ‘magma-rich’, and to contain SDRs and HVLCBs (Geoffroy et al., 2001; Breivik et al., 2012; Keen et al., 2012; Magee et al., 2016; Petersen and Schiffer, 2016; Larsen et al., 2016).

An early, coherent magmatic province in the North Atlantic realm was the Permo-Carboniferous Skagerrak LIP found in southern Sweden and Norway, Denmark, northern-central Europe and the British Isles (Heeremans et al., 2004; McCann et al., 2006). This igneous province was coeval with a general period of tectonic unrest and magmatic hyperactivity in Europe, possibly connected to the collapse of the Variscides that might have included extreme lithospheric thinning and delamination (Doblas et al., 1998; Timmerman et al., 2009; McCann et al., 2006; Meier et al., 2016).

Pre-breakup magmatism, likely associated with lithospheric thinning and rifting, occurs across the North Atlantic region in disparate occurrences, typically as small-fraction melts from the Late Triassic to the Cretaceous (Helwig et al., 1974; King and McMillan, 1975; Tappe et al., 2007; Larsen et al., 2009; Peace et al., 2016; Peace et al., 2018c; Peace et al., 2018d). These igneous rocks do not comprise a coherent magmatic province, but rather small-volume, distributed melts (e.g., lamprophyre dykes in West Greenland and Newfoundland; Helwig et al., 1974; Larsen et al., 2009). They demonstrate that significant lithospheric extension was likely widespread across the proto-North Atlantic region as far back as the Late Triassic (Larsen et al., 2009).

During and after breakup, widespread magmatism formed the North Atlantic Igneous Province (NAIP) (White, 1988; Upton, 1988; Saunders et al., 1997; Meyer et al., 2007; Storey et al., 2007; Hansen et al., 2009; Wilkinson et al., 2016; Á Horni et al., 2017). The NAIP is a classic LIP (Bryan and Ernst, 2008; Hansen et al., 2009) that comprises the voluminous Palaeogene igneous rocks of the East Greenland margin (Tegner et al., 1998), NW European margin (Melankholina, 2008), and JMMC (Breivik et al., 2012). To the west of Greenland, in the Davis Strait and on Baffin Island, other Palaeogene igneous rocks contribute to the NAIP (Clarke and Upton, 1971; Upton, 1988; Tegner et al., 2008; Hansen et al., 2009; Gaina et al., 2009; Nelson et al., 2015; Clarke and Beutel, this volume).

Distribution of NAIP volcanism is highly asymmetric between conjugate margins and the more magmatic margins may be associated with thicker lithosphere (Á Horni et al., 2017). Significantly more volcanism occurs south of the GFR than to the north (Schiffer et al., 2015; Á Horni et al., 2017). Petrologically, NAIP igneous rocks are highly diverse and include tholeiitic and alkali basalts, nepheline- and quartz-syenites, nephelinites, and carbonatites (Holbrook et al., 2001). NAIP igneous rocks are also highly variable in structure and include dykes, and sills (Magee et al., 2014), seaward-dipping reflectors (SDRs) (Larsen and Saunders, 1998), high-velocity lower crustal bodies (Funck et al., 2007), seamounts (Jones et al., 1974), and subaerial flows (Wilkinson et al., 2016; Á Horni et al., 2017).

Although the NAIP is often considered to comprise all pre-, syn- and post-breakup magmas, some are not generally included. For example, the Vestbakken Volcanic Province, and its conjugate equivalent in NE Greenland, have been attributed to local tectonic processes associated with shear margin development and are generally not considered part of the NAIP (Hansen et al., 2009; Á Horni et al., 2017). Significant magmatism is detected by seismic reflection, gravity and magnetic surveys near the western termination of the Charlie-Gibbs Fracture Zone (CGFZ) in the form of multiple flows and seamounts that are not typically

considered part of NAIP (Pe-Piper et al., 2013; Keen et al., 2014). The basaltic ‘U-reflector’ sills offshore Newfoundland, which cover an area of c. 20,000 km², are also excluded from the NAIP (Karner and Shillington, 2005; Hart and Blusztajn, 2006; Deemer et al., 2010; Peace et al., 2017b). The logic of inclusion or exclusion of magmatism under the umbrella term NAIP becomes increasingly unclear when it is noted that the Cretaceous-aged Anton Dohrn and Rockall seamounts are considered to belong to NAIP (Hitchen et al., 1995; Morton et al., 1995). This casts doubt on the rationale behind inclusion of igneous rocks in the NAIP and has implications for the extent, timing, magmatic budget and duration of NAIP, which in turn affect models for the tectono-magmatic processes responsible for its development. Much previous work also associates this LIP with a unique geochemical signature, although it is, in fact, highly variable (Korenaga and Kelemen, 2000; Á Horni et al., 2017).

The area of the NAIP has been estimated to be 1.3×10^6 km², and its volume, which is problematic to assess, is suggested to have once been $5 - 10 \times 10^6$ km³ (Holbrook et al., 2001; Storey et al., 2007; Wilkinson et al., 2016). Holbrook et al. (2001) estimated that between breakup and magnetic Chron C23n, 10^7 km³ of igneous crust was produced. The West Greenland constituent of the NAIP (the West Greenland Volcanic Province; WGVP e.g., Gill et al., 1992) is estimated to cover 2.2×10^3 km² in area (Clarke and Pedersen, 1976; R  sager et al., 2003).

6.3 Timing of rifting and magmatism

The NAIP is thought to have involved two main periods of melt emplacement: 1) ca. 62-58 Ma and 2) ca. 57-53 Ma, with distinct peaks in productivity at ca. 60 Ma and ca. 55 Ma (Hansen et al., 2009). Distinct parts of the NAIP were emplaced at different times (Lundin and Dor  , 2005b). For example the British volcanic province (BVP) and the WGVP are mostly Early Palaeocene whereas NE Atlantic magmatism is predominantly Early Eocene (Lundin and Dor  , 2005b). A unifying genetic model must account for this variable spatiotemporal distribution (Lundin and Dor  , 2005b; Peace et al., 2017a).

Petersen et al. (2018) recently proposed a mechanism to explain the two-phase igneous activity associated with the NAIP based on numerical modelling. They propose that lithospheric delamination triggered by destabilisation of thickened and metamorphosed, high-density lower crust produced the first igneous peak by small scale convection induced by detachment of the lithosphere. A second, much more voluminous phase of melting occurred when sinking lithospheric blocks penetrated the lower mantle and induced return flow.

In summary, rifting and breakup of the North Atlantic region was accompanied by prolonged, variable and extensive magmatism, some of which is conventionally considered to be part of the NAIP and some of which is not. The distinction is apparently model-dependent, inviting reassessment of both model and categorisation of the magmas.

6.4 Kinematics of the North Atlantic rift – implications for breakup

The North Atlantic opened by south-to-north propagation from the Central Atlantic into the NW and NE Atlantic (Lundin, 2002; Barnett-Moore et al., 2018; Nirrengarten et al., 2018). This contradicts the hypothesis that rifting migrated away from the NAIP, including the WGVP (Lundin and Doré, 2005a; Peace et al., 2017a). On the contrary, rifting migrated towards it, at odds with a plume-driven continental breakup model (Foulger et al. this volume).

There is little evidence for a time-progressive hotspot track (Lundin and Doré, 2005a) as predicted for a plume (Lawver and Müller, 1994; O'Neill et al., 2005; Doubrovine et al., 2012; Mordret, 2018). Although the GIFR is commonly viewed as a plume track there is no seamount chain to support this (Lundin and Doré, 2005b; Foulger et al. this volume). Similarly, in the West Greenland area, Peace et al. (2017a) note that evidence for a distinctive hotspot track associated with the WGVP is vague and poorly constrained, and that rifting and breakup do not follow the predicted path of the proposed plume (Lundin and Doré, 2005a). Additionally, in an idealised plume model, a deep-seated mantle plume would be required to precisely follow lithospheric breakup (e.g., Steinberger et al., 2018) for it to have remained beneath the active spreading plate boundary since inception (Lundin and Doré, 2005b). However, in reality a hypothetical mantle plume may deviate from the idealised model due to a number of processes such as shear flow (Richards and Griffiths, 1988) and deflection around cratonic keels (Sleep et al., 2002).

As described above, extension and magmatism are widely documented prior to postulated plume arrival in the Early Cenozoic. Within the NAIP, the occurrence of significantly more volcanism south of the GIFR than to the north (Schiffer et al., 2015; Á Horni et al., 2017) is at odds with the radial distribution of magmatism predicted by in an idealised plume model.

In summary, breakup of the North Atlantic was a complex, polyphase process, accompanied by highly compositionally variable magmatic events that require numerous ad hoc embellishments of a deep mantle plume impingement model. We it has been suggested that continental breakup and associated magmatism across the North Atlantic region was driven by lithospheric processes associated with plate tectonics (Lundin and Doré, 2005a; Lundin and Doré, 2005b; Ellis and Stoker, 2014; Schiffer et al., 2015; Peace et al., 2017a; Schiffer et al., 2018b), and that mantle temperatures were likely only slightly, if at all, above ambient (Hole and Natland, this volume)

7.0 Discussion

Magmatism is mainly confined to active plate boundaries (i.e., spreading ridges and subduction zones) where plate tectonic processes are indisputably responsible (Kearey et al., 2009). It has been suggested that the same holds true for continental margins.

It was realised early that the dominant force driving plate motion is slab-pull, which is probably an order of magnitude stronger than other forces (Forsyth and Uyeda, 1975). This is

consistent with the observation that the speed with which plates move is related to the length of the subducting slab to which they are attached. Considerable work has been done subsequently to investigate this relationship, including study of the apparent east-west asymmetry in the global subduction slab system (Doglioni and Anderson, 2015) and the systematic westward migration of spreading ridges which imparts east-west asymmetry to the composition of the mantle (Chalot-Prat et al., 2017).

In addition, new plate boundaries must, from time to time, be created because the constantly evolving configuration of plates results in periodic annihilation of plate boundaries and transmutation of others (e.g., subduction of the Farallon ridge and replacement of that subduction zone with the San Andreas transform system). Like all cracks in brittle material, extensional plate boundaries are most easily formed by propagation along pre-existing zones of weakness (Holdsworth et al., 2001). The most susceptible zones may well lie in the continental lithosphere, in particular if that lithosphere has been pre-weakened by a long history of tectonic deformation (Butler et al., 1997; Armitage et al., 2010; Audet and Bürgmann, 2011; Petersen and Schiffer, 2016; Peace et al., 2018a). The spatial scaling of lithospheric processes such as rifting and delamination, the heterogeneity of mantle composition (Foulger et al., 2005a; Chalot-Prat et al., 2017) and the complexity of other influential factors such as structural inheritance can explain the great diversity observed along such boundaries (Petersen and Schiffer, 2016; Schiffer et al. this volume). The plate-driven rifting models suggests that continental breakup is initiated by extensional forces, accompanied by rift-shoulder uplift, and magmatism is related to the passive upwelling of local, relatively shallow asthenosphere (Menzies et al., 2002). The extensional forces result from far-field plate-tectonic reorganisations (Geoffroy, 2005).

Plume impingement models predict uplift, LIP-emplacement and rifting in rapid succession (White, 1988; Dam et al., 1998; Beniest et al., 2017; Steinberger et al., 2018). In such models, the bulk of the magmatic products are expected prior to and during the initial stages of rifting, shortly after plume impact. In an ideal, theoretical case, stress in the overriding plate should be concentric around the location of plume impact (Franke, 2013) and lithosphere fragmentation should be initially radial, possibly via multiple rifts, and possibly forming triple junctions (Ernst and Buchan, 1997). Rifting is expected to initiate at, and propagate away from, the point of plume impact and LIP magmatism (Camp and Ross, 2004; Franke, 2013; Peace et al., 2017a). The regions we reviewed, associated with the Pangaea breakup, do not display these features.

7.1 Magmatism associated with Pangaea breakup

Emplacement of the CAMP LIP is the event traditionally associated with plume-driven models for formation of the Central Atlantic (Wilson, 1997). A centre at the Blake Plateau, near the modern-day Bahamas, has been proposed as the focus from which radiating rifts are expected (May, 1971). However, detailed observations do not fit this idealised model (McHone, 2000). Instead of post-dating and emanating from the CAMP LIP, continental rifting preceded it by ~30 Myr, started far to the south and propagated north where rifting continued for 5-10 Myrs after CAMP volcanism ceased (Olsen, 1997). The spatial pattern of

volcanism fails to match the predictions. Circum-Atlantic dykes are mostly oriented parallel to adjacent segments of the Central Atlantic rifted margins and a radial model has little support (McHone, 2000). Evidence for a plume track is also lacking since small-volume volcanic features on the Central Atlantic seafloor are much younger than CAMP volcanism, and may be entirely unrelated to CAMP and breakup.

A model for breakup as the culmination of long-term continental tectonic instability (Keppie, 2016), with rifting controlled by reactivation of older structures (Pique and Laville, 1996), and magmas tapped from the asthenosphere, explains the observations more easily (McHone, 2000). The Central Atlantic Ocean opened only after a protracted period of continental rifting (Davison, 2005). The continental margins re-opened sutures that had experienced at least two previous Wilson Cycles of suture and breakup, testifying to the controlling role of inheritance of pre-existing structure (Schiffer et al. this volume). CAMP magmatism comprised a brief phase of ~1 Myr of intense igneous productivity in the midst of a rifting event that lasted several tens of Myr. Volcanic rates were briefly so massive that production cannot be accounted for by any thermal-upwelling mechanism no matter how hot (Cordery et al., 1997). Furthermore, magmas were so widespread, extending throughout a region > 5,000 km wide (Denyszyn et al., 2018) penetrating far into the South American and African continents, that they cannot be attributed to a single source (McHone, 2003; Leleu et al., 2016). Instead, they require widespread lithospheric instability. The petrological diversity of CAMP lavas also cannot be explained by a single source but requires considerable mantle-source heterogeneity, possibly from recycled subducted slabs (Tollo and Gottfried, 1989).

Less information is available from the Western Somali and Mozambique basins which record the breakup of East and West Gondwana (Phethean et al., 2016). More detail needs to be known about the chronological relationships between tectonism and volcanism in the Mwenezi triple junction and Karoo rift and LIP in order to fully test the plume- and plate-driven hypotheses. It is clear, however, that in keeping with observations elsewhere, tectonic unrest was ongoing, with occasional phases of inactivity, in the region since the Early Permian, over 100 Myr before Jurassic breakup (Macgregor, 2018). Thus, the structures along which breakup-related magmatism occurred predated breakup by many millions of years. For example, many of the dykes in the Okavango swarm were formed in the Proterozoic, and share geochemical affinities with the Mesozoic breakup-related intrusives. This suggests a long-lived volcanic lithospheric feature and source since the region must have moved relative to the deeper mantle in the interim period. Evidence for extensive lateral flow of magmas at the time of breakup testifies to distributed sources rather than a single centre, e.g., at the Mwenezi triple junction. Furthermore, breakup and formation of the ocean basins did not radiate from the Mwenezi triple junction. Instead the evidence available suggests instead that breakup-related rifting migrated towards the triple junction. The close proximity of volcanic margins with SDRs and magma-poor margins is incompatible with a single, large-scale source.

Considerably more is known about the opening of the South Atlantic and the chronology and composition of lavas of the Parana-Etendeka LIP (Foulger, 2017). This region is associated

with the Cretaceous disintegration of West Gondwana and it exhibits extensive volcanic margins and SDRs (Franke et al., 2010). In plume models, the large, well-studied Paraná–Etendeka LIP in Brazil and Namibia is attributed to the head of a plume currently beneath Tristan da Cunha (Peate, 1997).

Since the proposal that South Atlantic breakup was plume-driven, a great deal of new and detailed information has accumulated from numerous marine geophysical experiments (Franke et al., 2007; Franke et al., 2010; Foulger, 2017). In addition, the structure and geochemistry of Paraná–Etendeka LIP lavas and postulated ‘plume tail’ volcanics on the Rio Grande- and Walvis ridges have been critically examined. Major chronological and spatial mismatches with the plume-driven breakup model have emerged. Rifting onset occurred long before the Paraná–Etendeka LIP was emplaced at ~132 Ma. Seafloor spreading in the southern South Atlantic in the Valanginian, at ~135 Ma and propagated northward in jumps, with brief hiatuses where the developing rift encountered barriers. Major volcanic margins were built, and thus breakup and large-scale magmatism was already well underway when the Paraná–Etendeka LIP was emplaced, at odds with the plume-driven breakup model. The rift unambiguously propagated toward the future location of the LIP, not away from it (Foulger, 2017).

Paraná lavas were emplaced in north-south-trending rift basins, testifying to ongoing extension prior to LIP emplacement. They erupted at the location of a major cross-cutting transverse lineament (Foulger, 2017), exploiting pre-existing structure. Of all continental LIPs, the geochemistry of the Paraná–Etendeka LIP is also perhaps the least equivocal that the lavas were derived from melted lithospheric mantle. In addition, recent detailed seismic surveys, both of the breakup margins and the African coastal part of the Walvis Ridge, show that spatially abrupt changes in magma volume are widespread (Franke et al., 2010).

The complex history of North Atlantic breakup and magmatism has been studied intensely for many decades, and is known in detail (Clarke and Upton, 1971; Srivastava and Roest, 1999; Hansen et al., 2009; Larsen et al., 2009; Nirrengarten et al., 2018; Schiffer et al. this volume; Hole and Natland, this volume). Volcanism has been widespread since the region initially began rifting in the Early Jurassic (or possibly Late Triassic; Larsen et al., 2009) followed by opening of the Labrador Sea (Chalmers and Pulvertaft, 2001). Early, relatively small-volume volcanism (Peace et al., 2018c) gave way to emplacement of massive volcanic margins with SDRs when spreading was transferred to the current NE Atlantic (Eldholm and Grue, 1994; Wilkinson et al., 2016).

Several magmatic events have been attributed to an Icelandic plume head, including the Siberian Traps (~251 Ma), volcanism in the Davis Strait (~62 Ma) (Gerlings et al., 2009) and widespread magmatism at the time of opening of the NE Atlantic Ocean (~54 Ma) (Steinberger et al., 2018). The latter two events accompanied lithospheric breakup and there is no evidence of a chronology of uplift followed by LIP volcanism and subsequent continental rifting (Foulger and Anderson, 2005; Peace et al., 2017a). On the contrary, tectonic unrest, continental extension and small-volume volcanism for several 100 Myr prior

to breakup is well-documented in Laurasia prior to breakup (Tappe et al., 2007; Larsen et al., 2009; Peace et al., 2016; Peace et al., 2018c).

Continental breakup along the Labrador Sea axis propagated to the region from the south (Chalmers and Pulvertaft, 2001; Peace et al., 2018a), and considerable magmatism occurred prior to emplacement of the magmas usually attributed to a plume head (McWhae et al., 1980; Larsen et al., 2009). At the Davis Strait and the GIFR, that magmatism occurred at locations where propagating breakup rifts encountered barriers that stalled progress (Peace et al., 2017a). In the case of the GIFR, a major focus of plume models (Foulger et al. this volume), volcanism developed at a locality where rifts propagating from both north and south were unable to break through transverse inherited orogenic structures.

7.2 Summary of spatial-temporal and magmatic-lithospheric relationships

All the locations reviewed herein show evidence for prolonged phases of rifting prior to LIP magmatism and breakup. In many cases, this rifting is thought to be genetically linked to breakup (e.g. rifting prior to the opening of the North Atlantic; e.g., Péron-Pinvidic et al., 2017). At other locations earlier rifting events may have been unassociated with the final breakup episode and the production of the first true oceanic crust. In all cases reviewed here, the onset of LIP magmatism and often eruption of the main volume significantly overlapped with or postdated SDR- and initial-oceanic-crust production. Such magmatism is inconsistent with plume impact driving sometimes long-lasting initial rifting. Instead, it suggests that magmatism was a consequence of the same mechanism that triggered by rifting and/or breakup.

Following plume arrival, widespread magmatism is predicted to occur in the region underlain by hot plume head material (Saunders et al., 1992; Saunders et al., 2007). This region is inferred to be circular, with a diameter of several 1000 kilometres in an idealised model. Buoyant melt is expected to intrude the crust radially, governed by the circular stress field generated by the impinging plume, and to form radial dyke swarms and sills, again in an idealised model. Lithospheric structure is expected to impose only secondary control (Saunders et al., 2007). The relatively small barriers presented by lithospheric inhomogeneities are expected to be overwhelmed by the much larger scale hot upwelling mantle material. These predictions are, however, not supported by observations of the disintegration of Pangaea. Instead, inherited lithospheric structure exerts a control, not only on the locus of breakup axes but also on the locations of magmatism including LIPs (Koopmann et al., 2014a; Peace et al., 2017a; Clarke and Beutel, this volume).

7.3 Plate-driven breakup

Plate-driven breakup models for the dispersal of Pangaea have been proposed. For example Keppie (2016) proposed that subduction at the peripheries of Pangaea can explain both the motion, deformation and dispersal of Pangaea with a single mechanism. In addition, much previous work links continental rifts and breakup on a range of scales and tectonic environments to pre-existing structures (Wu et al., 2016; Petersen and Schiffer, 2016; Peace

et al., 2018b; Schiffer et al., 2018; Collanega et al., 2019; Schiffer et al., this volume). A link between the intersection of propagating rifts with pre-existing suture zones and the production of magmatism has been suggested based primarily on geological observations from Atlantic margins and numerical modelling (Koopmann et al., 2014a; Schiffer et al., 2015; Peace et al., 2017a; Petersen et al., 2018). In these models, a barrier to rift propagation results in excess magmatism by blocking and diverting mantle flow beneath a propagating rift axis.

Observations from the locations reviewed here provide support for this model (Fig. 6). In the North, Central and South Atlantic and during breakup of East and West Gondwana, LIP locations coincide with large-scale, pre-existing lithospheric structures (Fig. 7). The origin, size and relative orientations of these structures with respect to approaching, propagating rifts is variable. Nevertheless, the association is systematic and warrants further investigation.

7.4 Ocean Island Chains

The mantle plume hypothesis for LIP volcanism predicts that, following plume-head-related flood-basalt eruptions, continued upwelling in the plume tail results in ongoing, small-volume magmatism (Saunders et al., 1992; White, 1992). The motion of the overhead plates relative to the “hotspot reference frame” transports these magmas away from the plume tail creating a time-progressive trail of volcanism that ages with increasing distance from the contemporary plume tail (e.g., Konrad et al., 2018). The existence of a time-progressive trail of volcanism, most clearly observed in the Hawaiian-Emperor island/seamount chains, was the single most influential factor in the development of the plume hypothesis and this characteristic is still considered by some to comprise the strongest evidence of a mantle plume (Morgan and Morgan, 2007).

This aspect of the plume model fits poorly the volcanism that followed emplacement of the LIPs discussed in this paper. Courtillot et al. (2003) review the features of postulated plumes worldwide. Of the four volcanic provinces we discuss (the CAMP, Karoo-Ferrar flood basalts, South Atlantic Igneous Province and NAIP), Courtillot et al. (2003) associate only the South Atlantic Igneous Province LIP flood-volcanism unambiguously with a time-progressive volcanic trail. Moreover, Courtillot et al. (2003) tentatively associate the CAMP with small volumes of volcanism at Fernando de Noronha on the Brazilian continental shelf and minor volcanism onshore. Considering the CAMP is thought to be one of the largest continental LIPs in the world (Denyszyn et al., 2018), the minimal evidence for plume tail volcanism makes the model doubtful. In addition, conflicting evidence from geochemistry (Lopes and Ulbrich, 2015) and the chronology of volcanism along archipelago of Fernando de Noronha (Knesel et al., 2011) casts further doubt on the applicability of an idealised plume model. The Karoo-Ferrar flood basalts are tentatively associated with a postulated plume currently centred beneath Crozet/Prince Edward Island (Courtillot et al., 2003). The volcanics that represent the best candidates for a time-progressive trail extending from that region comprise a ~200-km-wide archipelago of five island groups across which recent volcanism is widespread and evidence for systematic time-progression sparse. However, the oldest

volcanism known is ~9 Ma (Verwoerd et al., 1990) and there is no apparent link with the ~185–177 Ma Karoo–Ferrar flood basalts.

There is evidence for some age progression in volcanics in the South Atlantic. Proposed plume-tail volcanism comprises the Rio Grande Rise, the Walvis aseismic ridge and the associated Guyot Province that extends from the Etendeka continental flood basalts in Namibia to the volcanically active island of Tristan da Cunha. Reported ages range from 114 Ma near Namibia to 58–72 Ma at the SW end of the Walvis Ridge, and to 80–87 Ma for the Rio Grande Rise, which is believed to represent the counterpart of the Walvis Ridge on the South American Plate (Rohde et al., 2013). Age-progressive dates are obtained from the Walvis Ridge (O'Connor and Jokat, 2015) but there is little corresponding evidence from the Rio Grande Rise. On the contrary, continental material has recently been observed there, suggesting that the Rise is possibly a micro-continental fragment (Sager, 2014) that could have been isolated by a series of eastward ridge jumps (Graça et al., 2019).

In the NAIP the voluminous flood volcanism that formed the North Atlantic passive margins, is popularly attributed to a plume head (e.g., Chalmers et al., 1995; Gill et al., 1995; Steinberger et al., 2018). However, it is associated with no observed time-progressive volcanic trail (Peace et al., 2017a; Foulger et al. this volume). The GIFR is often attributed to this but supporting evidence is lacking (Foulger et al. this volume). Very few seamounts occur on the GIFR (Gaina et al., 2017a) and few reliable dates are available. The GIFR is time-progressive only in the same sense as the ocean floor, and it is interpreted to have formed as a consequence of prolonged, highly volcanic lithospheric extension (Foulger et al. this volume).

8.0 Concluding remarks

This review highlights significant spatial-temporal variability between the locations of LIPs and the initiation points of Pangaea disintegration. None of the regions we review fit comfortably a plume-driven breakup model that predicts pre-breakup magmatism, plume tail eruptions producing ocean island chains, and rifting radiating from the point of plume impact. In contrast, most show multiple characteristics that are not fully compatible with this model, including a reverse chronology of uplift, magmatism and rifting, and rifting propagating towards LIPs. The idealised, generic plume-impingement model thus has difficulties fully explaining the dispersal of Pangaea and associated magmatism.

Rifting and breakup driven primarily by far-field extensional forces, with magmatism occurring as a consequence, under strong lithospheric control, is much more consistent with observations that are common throughout the regions we review. These observations include:

- The supercontinent in the neighbourhood of future breakup experienced almost continuous unrest, including extension and continental rifting and small-volume magmatism for long periods prior to breakup (10s to 100s of Myr).
- Evidence for pre-LIP uplift is lacking. Margin uplift contemporaneous with breakup is consistent with rift-shoulder uplift.

- Magmatism followed pre-existing structures that may have experienced volcanism before.
- The source of magmas was distributed. Magmas did not arise from a single centre.
- Large-volume magmatism (LIP emplacement) occurred distal to simultaneous breakup-related rifting, which tended to migrate towards the new LIP.
- The geochemistry of LIP lavas, in particular their Ti contents, suggest a source in the lithospheric mantle.
- The very rapid emplacement of the LIP lavas, with rates on the order of 10^6 km^3 in 1 Myr, are incompatible with melt production on the same time-scale as eruption. They can essentially only be explained as the draining of pre-existing melt reservoirs that accumulated over a longer period of time than it took to drain them (Silver et al., 2006).

Other factors that likely exert some influence include spatially and temporally variable mantle-source temperature and composition as rifts propagate laterally and asthenosphere wells up from beneath lithosphere initially 100-200 km thick (Brandl et al., 2013; Langmuir, 2013). Other processes that may encourage or be consequential to rifting include delamination of lower lithosphere, small-scale convection (King and Anderson, 1995; King and Anderson, 1998; Simon et al., 2009; Peace et al., 2017a) along Archean craton boundaries and fragmentation of the new margins to form microcontinents (Schiffer et al., 2018). In conclusion, a lithosphere-centred model for Pangaea breakup is the simplest that can explain the primary, common features expressed along the passive margins of the former supercontinent Pangaea.

9.0 Acknowledgements

We acknowledge the Durham North Atlantic Workshop group and the meetings held at Durham University, UK between 2016 and 2018. Alexander L. Peace's postdoctoral fellowship at Memorial University of Newfoundland, Canada was funded by the Hibernia Project Geophysics Support Fund. Christian Schiffer's postdoctoral fellowship at Durham University was funded by the Carlsberg Foundation. We would also like to thank the special issue editor Carlo Doglioni, in addition to the constructive and thoughtful reviews provided by Scott King and an anonymous reviewer that greatly improved the quality of this contribution. Finally, Nick Kusznir is acknowledged for constructive comments on an earlier draft of this paper.

10.0 References

- Á Horni, J., Hopper, J.R., Blischke, A., Geisler, W.H., Stewart, M., McDermott, K., Judge, M., Erlendsson, Ö., and Ártíng, U., 2017, Regional distribution of volcanism within the North Atlantic Igneous Province: Geological Society, London, Special Publications, v. 447, no. August, p. SP447.18, doi: 10.1144/SP447.18.
- Abdelmalak, M.M., Geoffroy, L., Angelier, J., Bonin, B., Callot, J.P., Gélard, J.P., and Aubourg, C., 2012, Stress fields acting during lithosphere breakup above a melting mantle: A case example in West Greenland: Tectonophysics, v. 581, p. 132–143, doi:

10.1016/j.tecto.2011.11.020.

- Abdelmalak, M.M., Planke, S., Polteau, S., Hartz, E.H., Faleide, J.I., Tegner, C., Jerram, D.A., Millett, J.M., and Myklebust, R., 2018, Breakup volcanism and plate tectonics in the NW Atlantic: Tectonophysics, doi: 10.1016/j.tecto.2018.08.002.
- Ady, B.E., and Whittaker, R.C., 2018, Examining the influence of tectonic inheritance on the evolution of the North Atlantic using a palinspastic deformable plate reconstruction: , doi: 10.1144/SP470.9.
- Andersen, T.B., Jamtveit, B., Dewey, J., and Swensson, E., 1991, Subduction and eduction of continental crust: major mechanisms during continent- continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides: *Terra Nova*, v. 3, no. 3, p. 303–310, doi: 10.1111/j.1365-3121.1991.tb00148.x.
- Anderson, D.L., 1994, The sublithospheric mantle as the source of continental flood basalts; the case against the continental lithosphere and plume head reservoirs: *Earth and Planetary Science Letters*, v. 123, no. 1, p. 269–280, doi: [https://doi.org/10.1016/0012-821X\(94\)90273-9](https://doi.org/10.1016/0012-821X(94)90273-9).
- Armitage, J.J., Collier, J.S., and Minshull, T.A., 2010, The importance of rift history for volcanic margin formation.: *Nature*, v. 465, no. 7300, p. 913–917, doi: 10.1038/nature09063.
- Audet, P., and Bürgmann, R., 2011, Dominant role of tectonic inheritance in supercontinent cycles: *Nature Geoscience*, v. 4, no. 3, p. 184–187, doi: 10.1038/geo1080.
- Austin, J.A., and Uchupi, E., 1982, Continental-oceanic crustal transition off Southwest Africa: *AAPG Bulletin*, v. 66, no. 9, p. 1328–1347.
- Balduzzi, A., Msaky, E., Trincianti, E., and Manum, S.B., 1992, Mesozoic Karoo and post-Karoo formations in the Kilwa area, southeastern Tanzania - a stratigraphic study based on palynology, micropaleontology and well log data from the Kizimbani Well: *Journal of African Earth Sciences (and the Middle East)*, v. 15, no. 3, p. 405–427, doi: [https://doi.org/10.1016/0899-5362\(92\)90025-8](https://doi.org/10.1016/0899-5362(92)90025-8).
- Balmino, G., Briais, A., Kuhn, M., Peyrefitte, A., Vales, N., Biancale, R., Gabalda, G., Reinquin, F., and Sarrailh, M., 2012, World gravity map. Commission for the geological map of the world. Eds: BGI-CGMW-CNES-IRD, Paris.
- Barnett-Moore, N., Müller, R.D., Williams, S., Skogseid, J., and Seton, M., 2018, A reconstruction of the North Atlantic since the earliest Jurassic: *Basin Research*, v. 30, p. 160–185, doi: 10.1111/bre.12214.
- Bauer, K., Neben, S., Schreckenberger, B., Emmermann, R., Hinz, K., Fechner, N., Gohl, K., Schulze, A., Trumbull, R.B., and Weber, K., 2000, Deep structure of the Namibia continental margin as derived from integrated geophysical studies: *Journal of Geophysical Research: Solid Earth*, v. 105, no. B11, p. 25829–25853, doi: 10.1029/2000JB900227.
- Becker, K., Franke, D., Schnabel, M., Schreckenberger, B., Heyde, I., and Krawczyk, C.M., 2012, The crustal structure of the southern Argentine margin: *Geophysical Journal*

- International, v. 189, no. 3, p. 1483–1504, doi: 10.1111/j.1365-246X.2012.05445.x.
- Becker, K., Franke, D., Trumbull, R., Schnabel, M., Heyde, I., Schreckenberger, B., Koopmann, H., Bauer, K., Jokat, W., and Krawczyk, C.M., 2014, Asymmetry of high-velocity lower crust on the South Atlantic rifted margins and implications for the interplay of magmatism and tectonics in continental breakup: *Solid Earth*, v. 5, no. 2, p. 1011–1026, doi: 10.5194/se-5-1011-2014.
- Becker, K., Tanner, D.C., Franke, D., and Krawczyk, C.M., 2016, Fault-controlled lithospheric detachment of the volcanic southern South Atlantic rift: *Geochemistry, Geophysics, Geosystems*, p. 1–8, doi: 10.1002/2015GC006081.
- Ben-Avraham, Z., Hartnady, C.J.H., and Kitchin, K.A., 1997, Structure and tectonics of the Agulhas-Falkland fracture zone: *Tectonophysics*, v. 282, no. 1–4, p. 83–98.
- Beniest, A., Koptev, A., Leroy, S., Sassi, W., and Guichet, X., 2017, Two-branch break-up systems by a single mantle plume: Insights from numerical modeling: *Geophysical Research Letters*, doi: 10.1002/2017GL074866.
- Bensalah, M.K., Youbi, N., Mahmoudi, A., Bertrand, H., Mata, J., El Hachimi, H., Madeira, J., Martins, L., Marzoli, A., Bellon, H., Medina, F., Karroum, M., L., K., and Ben Abbou, M., 2011, The Central Atlantic Magmatic Province (CAMP) volcanic sequences of Berrechid and Doukkala (Western Mesta, Morocco): *Volcanology and geochemistry. : Comunicações Geológicas*, v. 98, p. 15–27.
- Benson, R.N., 2003, Age Estimates of the Seaward-Dipping Volcanic Wedge, Earliest Oceanic Crust, and Earliest Drift-Stage Sediments Along the North American Atlantic Continental Margin, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, *American Geophysical Union*, p. 61–75.
- Bertrand, H., and Coffrant, D., 1977, Geochemistry of tholeiites from North-East American margin; correlation with Morocco: *Contributions to Mineralogy and Petrology*, v. 63, no. 1, p. 65–74, doi: 10.1007/BF00371676.
- Beutel, E.K., Nomade, S., Fronabarger, A.K., and Renne, P.R., 2005, Pangea's complex breakup: A new rapidly changing stress field model: *Earth and Planetary Science Letters*, v. 236, no. 1–2, p. 471–485, doi: 10.1016/j.epsl.2005.03.021.
- Biari, Y., Klingelhoefer, F., Sahabi, M., Funck, T., Benabdellouahed, M., Schnabel, M., Reichert, C., Gutscher, M.A., Bronner, A., and Austin, J.A., 2017, Opening of the central Atlantic Ocean: Implications for geometric rifting and asymmetric initial seafloor spreading after continental breakup: *Tectonics*, p. 1–22, doi: 10.1002/2017TC004596.
- Bird, D.E., and Hall, S.A., 2016, Early seafloor spreading in the South Atlantic: new evidence for M-series magnetochrons north of the Rio Grande Fracture Zone: *Geophysical Journal International*, v. 206, no. 2, p. 835–844.
- Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D. V., Puffer, J., McHone, G., Rasbury, E.T., and Et-Touhami, M., 2013, Zircon U-Pb Geochronology Links the End-Triassic Extinction with the Central Atlantic Magmatic Province: *Science*, v. 340, no. 6135, p. 941 LP-945.

- Blakey, R.C., and Wong, T.E., 2003, Carboniferous–Permian paleogeography of the assembly of Pangaea: Proceedings of the XVth International Congress on Carboniferous and Permian Stratigraphy, p. 16.
- Blischke, A., Gaina, C., Hopper, J.R., Péron-Pinvidic, G., Brandsdóttir, B., Guarnieri, P., Erlendsson, Ö., and Gunnarsson, K., 2016, The Jan Mayen microcontinent: an update of its architecture, structural development and role during the transition from the Ægir Ridge to the mid-oceanic Kolbeinsey Ridge: The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution, v. 447, no. 1, p. 299–337.
- Blischke, A., Stoker, M.S., Brandsdóttir, B., Hopper, J.R., Peron-Pinvidic, G., Ólavsdóttir, J., and Japsen, P., 2019, The Jan Mayen microcontinent's Cenozoic stratigraphic succession and structural evolution within the NE-Atlantic: Marine and Petroleum Geology,.
- Boillot, G., and Malod, J., 1988, The north and north-west Spanish Continental Margin: a review: Rev. Soc. Geol. España, v. 1, no. 3–4, p. 295–316.
- Bonath, E., 1990, Not so hot" hot spots" in the oceanic mantle: Science, v. 250, no. 4977, p. 107–111.
- Bradley, D.C., 2008, Passive margins through earth history: Earth-Science Reviews, v. 91, no. 1–4, p. 1–26, doi: 10.1016/j.earscirev.2008.08.001.
- Brandl, P.A., Regelous, M., Beier, C., and Haase, K.M., 2013, High mantle temperatures following rifting caused by continental insulation: Nature Geoscience, v. 6, no. 5, p. 391.
- Breivik, A.J., Mjelde, R., Faleide, J.I., and Murai, Y., 2012, The eastern Jan Mayen microcontinent volcanic margin: Geophysical Journal International, v. 188, no. 3, p. 798–818, doi: 10.1111/j.1365-246X.2011.05307.x.
- Le Breton, E., Cobbold, P.R., Dauteuil, O., and Lewis, G., 2012, Variations in amount and direction of seafloor spreading along the northeast Atlantic Ocean and resulting deformation of the continental margin of northwest Europe: Tectonics, v. 31, no. 5, p. 1–16, doi: 10.1029/2011TC003087.
- Bryan, S.E., and Ernst, R.E., 2008, Revised definition of Large Igneous Provinces (LIPs): Earth-Science Reviews, v. 86, no. 1–4, p. 175–202, doi: 10.1016/j.earscirev.2007.08.008.
- Butler, R.W.H., Holdsworth, R.E., and Lloyd, G.E., 1997, The role of basement reactivation in continental deformation: Journal of the Geological Society, v. 154, no. 1, p. 69–71, doi: 10.1144/gsjgs.154.1.0069.
- Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: Journal of Geophysical Research: Solid Earth, v. 109, no. B8.
- Campbell, I.H., and Kerr, A.C., 2007, Testing the plume theory: Chemical Geology, v. 241, no. 3–4, p. 153–176, doi: 10.1016/j.chemgeo.2007.01.024.

- Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., and Hancox, P.J., 2005, The Karoo basins of south-central Africa: *Journal of African Earth Sciences*, v. 43, no. 1, p. 211–253, doi: <https://doi.org/10.1016/j.jafrearsci.2005.07.007>.
- Cawood, P.A., and Pisarevsky, S.A., 2006, Was Baltica right-way-up or upside-down in the Neoproterozoic? *Journal of the Geological Society*, v. 163, no. 5, p. 753 LP-759.
- Chalmers, J.A., 1997, The continental margin off southern Greenland: along-strike transition from an amagmatic to a volcanic margin: *Journal of the Geological Society*, v. 154, no. 3, p. 571–576, doi: 10.1144/gsjgs.154.3.0571.
- Chalmers, J.A., Larsen, L.M., and Pedersen, A.K., 1995, Widespread Palaeocene volcanism around the northern North Atlantic and Labrador Sea: evidence for a large, hot, early plume head: *Journal of the Geological Society*, v. 152, no. 6, p. 965–969, doi: 10.1144/GSL.JGS.1995.152.01.14.
- Chalmers, J.A., and Laursen, K.H., 1995, Labrador Sea: the extent of continental and oceanic crust and the timing of the onset of seafloor spreading: *Marine and Petroleum Geology*, v. 12, no. 2, p. 205–217, doi: 10.1016/0264-8172(95)92840-S.
- Chalmers, J.A., and Pulvertaft, T.C.R., 2001, Development of the continental margins of the Labrador Sea: a review: *Geological Society, London, Special Publications*, v. 187, no. 1, p. 77–105, doi: 10.1144/GSL.SP.2001.187.01.05.
- Chalot-Prat, F., Doglioni, C., and Falloon, T., 2017, Westward migration of oceanic ridges and related asymmetric upper mantle differentiation: *Lithos*, v. 268–271, p. 163–173, doi: 10.1016/j.lithos.2016.10.036.
- Chian, D., Keen, C., Reid, I., and Loudon, K.E., 1995, Evolution of nonvolcanic rifted margins: new results from the conjugate margins of the Labrador Sea: *Geology*, v. 23, no. 7, p. 589–592, doi: 10.1130/0091-7613(1995)023<0589:EONRMN>2.3.CO;2.
- Cirilli, S., Marzoli, A., Tanner, L., Bertrand, H., Buratti, N., Jourdan, F., Bellieni, G., Kontak, D., and Renne, P.R., 2009, Latest Triassic onset of the Central Atlantic Magmatic Province (CAMP) volcanism in the Fundy Basin (Nova Scotia): New stratigraphic constraints: *Earth and Planetary Science Letters*, v. 286, no. 3–4, p. 514–525, doi: 10.1016/j.epsl.2009.07.021.
- Clarke, D.B., and Beutel, E.K. Davis Strait Paleocene Picrites: Products of a Plume or Plates? *Earth-Science Reviews*,.
- Clarke, D.B., and Beutel, E.K., 2019, Davis Strait Paleocene Picrites: Products of a Plume or Plates? *Earth-Science Reviews*, doi: 10.1016/j.earscirev.2019.01.012.
- Clarke, D.B., and Pedersen, A.K., 1976, Tertiary volcanic province of West Greenland, *in* *Geology of Greenland*, Geological Survey of Greenland, p. 365–385.
- Clarke, D.B., and Upton, B.G.J., 1971, Tertiary Basalts of Baffin Island: Field relations and tectonic setting.: *Canadian Journal of Earth Sciences*, v. 8, no. 2, p. 248–258, doi: 10.1139/e71-025.

- Clemson, J., Cartwright, J., and Booth, J., 1997, Structural segmentation and the influence of basement structure on the Namibian passive margin: *Journal of the Geological Society*, v. 154, no. 3, p. 477 LP-482, doi: 10.1144/gsjgs.154.3.0477.
- Cocks, L.R.M., and Torsvik, T.H., 2006, European geography in a global context from the Vendian to the end of the Palaeozoic: *Geological Society, London, Memoirs*, v. 32, no. 1, p. 83 LP-95.
- Cocks, L.R.M., and Torsvik, T.H., 2007, Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic: *Earth-Science Reviews*, v. 82, no. 1, p. 29–74, doi: <https://doi.org/10.1016/j.earscirev.2007.02.001>.
- Cocks, L.R.M., and Torsvik, T.H., 2011, The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins: *Earth-Science Reviews*, v. 106, no. 1–2, p. 1–51, doi: 10.1016/j.earscirev.2011.01.007.
- Coffin, M.F., and Rabinowitz, P.D., 1992, The Mesozoic East African and Madagascan Conjugate Continental Margins: Stratigraphy and Tectonics, *in* Watkins, J.S., Zhiqiang, F., and McMillen, K.J. eds., *Geology and Geophysics of Continental Margins*, American Association of Petroleum Geologists.
- Coffin, M.F., Rabinowitz, P.D., and Houtz, R.E., 1986, Crustal structure in the Western Somali Basin: *Geophysical Journal International*, v. 86, no. 2, p. 331–369.
- Collanega, L., Jackson, C.A., Bell, R.E., Coleman, A.J., Lenhart, A., and Breda, A., 2019, Normal fault growth influenced by basement fabrics: the importance of preferential nucleation from pre- existing structures: *Basin Research*.
- Collier, J.S., McDermott, C., Warner, G., Gyori, N., Schnabel, M., McDermott, K., and Horn, B.W., 2017, New constraints on the age and style of continental breakup in the South Atlantic from magnetic anomaly data: *Earth and Planetary Science Letters*, v. 477, p. 27–40, doi: 10.1016/j.epsl.2017.08.007.
- Comin-Chiaromonti, P., De Min, A., Girardi, V.A. V, and Ruberti, E., 2011, Post-Paleozoic magmatism in Angola and Namibia: A review, *in* Beccaluva, L., Bianchini, G., and Wilson, M. eds., *Geological Society of America*.
- Cordery, M.J., Davies, G.F., and Campbell, I.H., 1997, Genesis of flood basalts from eclogite- bearing mantle plumes: *Journal of Geophysical Research: Solid Earth*, v. 102, no. B9, p. 20179–20197.
- Corner, B., Cartwright, J., and Swart, R., 2002, Volcanic passive margin of Namibia: A potential fields perspective: *Geological Society of America Special Paper*, v. 362, p. 203–220, doi: 10.1130/0-8137-2362-0.203.
- Courtillot, V.E., 1980, Opening of the Gulf of Aden and Afar by progressive tearing: *Physics of the Earth and Planetary Interiors*, v. 21, no. 4, p. 343–350.
- Courtillot, V., Davaille, A., Besse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: *Earth and Planetary Science Letters*, v. 205, no. 3–4, p. 295–308, doi: 10.1016/S0012-821X(02)01048-8.

- Cowie, P.A., Underhill, J.R., Behn, M.D., Lin, J., and Gill, C.E., 2005, Spatio-temporal evolution of strain accumulation derived from multi-scale observations of Late Jurassic rifting in the northern North Sea: A critical test of models for lithospheric extension: *Earth and Planetary Science Letters*, v. 234, no. 3–4, p. 401–419, doi: 10.1016/j.epsl.2005.01.039.
- Cox, K.G., 1992, Karoo igneous activity, and the early stages of the break-up of Gondwanaland: Geological Society, London, Special Publications, v. 68, no. 1, p. 137–148.
- Dalziel, I.W.D., Lawver, L.A., and Murphy, J.B., 2000, Plumes, orogenesis, and supercontinental fragmentation: *Earth and Planetary Science Letters*, v. 178, no. 1–2, p. 1–11, doi: 10.1016/S0012-821X(00)00061-3.
- Dam, G., Larsen, M., and Søndersholm, M., 1998, Sedimentary response to mantle plumes: Implications from Paleocene onshore successions, West and East Greenland: *Geology*, v. 26, no. 3, p. 207–210, doi: 10.1130/0091-7613(1998)026<0207:SRTMPI>2.3.CO;2.
- Davies, J.H.F.L., Marzoli, A., Bertrand, H., Youbi, N., Ernesto, M., and Schaltegger, U., 2017, End-Triassic mass extinction started by intrusive CAMP activity: *Nature Communications*, v. 8, p. 15596.
- Davis, J.K., Bécel, A., and Buck, W.R., 2018, Estimating emplacement rates for seaward-dipping reflectors associated with the US East Coast Magnetic Anomaly: *Geophysical Journal International*, v. 215, no. 3, p. 1594–1603.
- Davis, J.K., Lawver, L.A., Norton, I.O., and Gahagan, L.M., 2016, New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean: *Gondwana Research*, v. 34, p. 16–28, doi: <https://doi.org/10.1016/j.gr.2016.02.010>.
- Davison, I., 2005, Central Atlantic margin basins of North West Africa: Geology and hydrocarbon potential (Morocco to Guinea): *Journal of African Earth Sciences*, v. 43, no. 1–3, p. 254–274, doi: 10.1016/j.jafrearsci.2005.07.018.
- Davison, I.A.N., 1997, Wide and narrow margins of the Brazilian South Atlantic: *Journal of the Geological Society*, v. 154, no. 3, p. 471–476, doi: 10.1144/gsjgs.154.3.0471.
- Davison, I., and Steel, I., 2018, Geology and hydrocarbon potential of the East African continental margin: a review: *Petroleum Geoscience*, v. 24, no. 1, p. 57–91.
- Deckart, K., Bertrand, H., and Liégeois, J.P., 2005, Geochemistry and Sr, Nd, Pb isotopic composition of the Central Atlantic Magmatic Province (CAMP) in Guyana and Guinea: *Lithos*, v. 82, no. 3–4 SPEC. ISS., p. 289–314, doi: 10.1016/j.lithos.2004.09.023.
- Deemer, S., Hurich, C., and Hall, J., 2010, Post-rift flood-basalt-like volcanism on the Newfoundland Basin nonvolcanic margin: The U event mapped with spectral decomposition: *Tectonophysics*, v. 494, no. 1–2, p. 1–16, doi: 10.1016/j.tecto.2010.07.019.
- Deenen, M.H.L., Ruhl, M., Bonis, N.R., Krijgsman, W., Kuerschner, W.M., Reitsma, M., and van Bergen, M.J., 2010, A new chronology for the end-Triassic mass extinction: *Earth and Planetary Science Letters*, v. 291, no. 1, p. 113–125, doi:

<https://doi.org/10.1016/j.epsl.2010.01.003>.

- Delvaux, D., 2001, Karoo Rifting in Western Tanzania: Precursor of Gondwana Break-up? Contribution to Geology and Palaeontology of Gondwana in Honour of Helmut Wopfner, p. 111–125.
- Denyszyn, S.W., Fiorentini, M.L., Maas, R., and Dering, G., 2018, A bigger tent for CAMP: Geology, v. 49, no. 9, p. 823–826.
- Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, no. 6, p. 1123–1139, doi: 10.1029/TC007i006p01123.
- Dewey, J.F., Ryan, P.D., and Andersen, T.B., 1993, Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: the role of eclogites: Geological Society, London, Special Publications, v. 76, no. 1, p. 325–343, doi: 10.1144/GSL.SP.1993.076.01.16.
- Dietz, R.S., and Holden, J.C., 1970, Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to Present: Journal of Geophysical Research, v. 75, no. 26, p. 4939–4956, doi: 10.1029/JB075i026p04939.
- Doblas, M., Oyarzun, R., Lopez-Ruiz, J., Cebria, J.M., Youbi, N., Mahecha, V., Lago, M., Pocovi, A., and Cabanis, B., 1998, Permo-Carboniferous volcanism in Europe and northwest Africa: a superplume exhaust valve in the centre of Pangaea? Journal of African Earth Sciences, v. 26, no. 1, p. 89–99.
- Doglioni, C., and Anderson, D.L., 2015, Top-driven asymmetric mantle convection: The Geological Society of America, v. 71, no. 1, p. 51–63, doi: 10.1130/2015.2514(05).
- Doglioni, C., Green, D.H., and Mongelli, F., 2005, The Westward Drift of the Lithosphere: Society, v. 2388, no. 42, p. 735–749, doi: 10.1130/2005.2388(42).For.
- Doré, A.G., Lundin, E.R., Fichler, C., Olesen, O., Dore, A.G., Lundin, E.R., Fichler, C., and Olesen, O., 1997, Patterns of basement structure and reactivation along the NE Atlantic margin: Journal of the Geological Society, v. 154, no. 1, p. 85–92, doi: 10.1144/gsjgs.154.1.0085.
- Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., and Fichler, C., 1999, Principal tectonic events in the evolution of the northwest European Atlantic margin: Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, v. 5, p. 41–61, doi: 10.1144/0050041.
- Dobrovine, P. V., Steinberger, B., and Torsvik, T.H., 2012, Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans: Journal of Geophysical Research: Solid Earth, v. 117, no. B9.
- Dunlap, W.J., and Fossen, H., 1998, Early Paleozoic orogenic collapse, tectonic stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, southern Norway: Tectonics, v. 17, no. 4, p. 604–620, doi: 10.1029/98TC01603.
- Eagles, G., 2007, New angles on South Atlantic opening: Geophysical Journal International,

v. 168, no. 1, p. 353–361.

Eagles, G., and König, M., 2008, A model of plate kinematics in Gondwana breakup: *Geophysical Journal International*, v. 173, no. 2, p. 703–717.

Eddy, M.P., Jagoutz, O., and Ibañez-Mejia, M., 2017, Timing of initial seafloor spreading in the Newfoundland-Iberia rift: *Geology*, v. 45, no. 6, p. G38766.1, doi: 10.1130/G38766.1.

Eldholm, O., and Grue, K., 1994, North Atlantic volcanic margins: dimensions and production rates: *Journal of Geophysical Research*, v. 99, no. B2, p. 2955–2968, doi: 10.1029/93JB02879.

Elliott, G.M., Berndt, C., and Parson, L.M., 2009, The SW African volcanic rifted margin and the initiation of the Walvis Ridge, South Atlantic: *Marine Geophysical Researches*, v. 30, no. 3, p. 207–214, doi: 10.1007/s11001-009-9077-x.

Ellis, D., and Stoker, M.S., 2014, The Faroe-Shetland Basin: a regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean: *Geological Society, London, Special Publications*, v. 397, no. 1, p. 11–31, doi: 10.1144/SP397.1.

Encarnación, J., Fleming, T.H., Elliot, D.H., and Eales, H. V., 1996, Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana: *Geology*, v. 24, no. 6, p. 535–538, doi: 10.1130/0091-7613(1996)024<0535:SEOFAK>2.3.CO;2.

Engström, J., and Klint, K., 2014, Continental Collision Structures and Post-Orogenic Geological History of the Kangerlussuaq Area in the Southern Part of the Nagssugtoqidian Orogen, Central West Greenland: *Geosciences*, v. 4, p. 316–334, doi: 10.3390/geosciences4040316.

Ernst, R.E., 2014, Large igneous provinces: Cambridge University Press.

Ernst, R.E., and Buchan, K.L., 1997, Giant radiating dyke swarms: their use in identifying pre-Mesozoic large igneous provinces and mantle plumes: *Geophysical Monograph Series*, v. 100, p. 297–334.

Evain, M., Afilhado, A., Rigoti, C., Loureiro, A., Alves, D., Klingelhofer, F., Schnurle, P., Feld, A., Fuck, R., Soares, J., De Lima, M.V., Corela, C., Matias, L., Benabdellouahed, M., et al., 2015, Deep structure of the Santos Basin-São Paulo Plateau System, SE Brazil: *Journal of Geophysical Research B: Solid Earth*, v. 120, no. 8, p. 5401–5431, doi: 10.1002/2014JB011561.

Forsyth, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motion: *Geophysical Journal International*, v. 43, no. 1, p. 163–200.

Fossen, H., 2010, Extensional tectonics in the North Atlantic Caledonides: a regional view: *Geological Society, London, Special Publications*, v. 335, no. 1, p. 767 LP-793.

Foulger, G.R., 2017, Origin of the South Atlantic igneous province: *Journal of Volcanology and Geothermal Research*, doi: <https://doi.org/10.1016/j.jvolgeores.2017.09.004>.

- Foulger, G.R., and Anderson, D.L., 2005, A cool model for the Iceland hotspot: *Journal of Volcanology and Geothermal Research*, v. 141, no. 1–2, p. 1–22, doi: 10.1016/j.jvolgeores.2004.10.007.
- Foulger, G.R., Doré, A.G., Emeleus, C.H., Franke, D., Geoffroy, L., Gernigon, L., Hey, R., Holdsworth, R.E., Hole, M., Höskuldsson, Á., Julian, B., Kuszniir, N., Martinez, F., Natland, J.H., et al. A continental Greenland-Iceland-Faroe Ridge: *Earth-Science Reviews*,.
- Foulger, G.R., Natland, J.H., and Anderson, D.L., 2005a, A source for Icelandic magmas in remelted Iapetus crust: *Journal of Volcanology and Geothermal Research*, v. 141, no. 1–2, p. 23–44, doi: 10.1016/j.jvolgeores.2004.10.006.
- Foulger, G.R., Natland, J.H., and Anderson, D.L., 2005b, Genesis of the Iceland melt anomaly by plate tectonic processes: *SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA*, v. 388, p. 595.
- Franke, D., 2013, Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins: *Marine and Petroleum Geology*, v. 43, no. 0, p. 63–87, doi: 10.1016/j.marpetgeo.2012.11.003.
- Franke, D., Ladage, S., Schnabel, M., Schreckenberger, B., Reichert, C., Hinz, K., Paterlini, M., De Abelleira, J., and Siciliano, M., 2010, Birth of a volcanic margin off Argentina, South Atlantic: *Geochemistry, Geophysics, Geosystems*, v. 11, no. 2, doi: 10.1029/2009GC002715.
- Franke, D., Neben, S., Ladage, S., Schreckenberger, B., and Hinz, K., 2007, Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic: *Marine Geology*, v. 244, no. 1–4, p. 46–67, doi: 10.1016/j.margeo.2007.06.009.
- Frimmel, H.E., Fölling, P.G., and Diamond, R., 2001, Metamorphism of the Permo-Triassic Cape Fold Belt and its basement, South Africa: *Mineralogy and Petrology*, v. 73, no. 4, p. 325–346, doi: 10.1007/s007100170005.
- Frizon De Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., and De Clarens, P., 2015, Style of rifting and the stages of Pangea breakup: *Tectonics*, v. 34, no. 5, p. 1009–1029, doi: 10.1002/2014TC003760.
- Fromm, T., Planert, L., Jokat, W., Ryberg, T., Behrmann, J.H., Weber, M.H., and Haberland, C., 2015, South Atlantic opening: A plume-induced breakup? *Geology*, v. 43, no. 10, p. 931–934.
- Funck, T., Jackson, H.R., Loudon, K.E., and Klingelhofer, F., 2007, Seismic study of the transform-rifted margin in Davis Strait between Baffin Island (Canada) and Greenland: What happens when a plume meets a transform: *Journal of Geophysical Research: Solid Earth*, v. 112, no. 4, p. B04402, doi: 10.1029/2006JB004308.
- Gaina, C., Blischke, A., Geissler, W.H., Kimbell, G.S., and Erlendsson, Ö., 2017a, Seamounts and oceanic igneous features in the NE Atlantic: a link between plate motions and mantle dynamics: *Geological Society, London, Special Publications*, v. 447, no. 1, p. 419–442, doi: 10.1144/SP447.6.

- Gaina, C., Gernigon, L., and Ball, P., 2009, Palaeocene-Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent: *Journal of the Geological Society*, v. 166, no. 4, p. 601–616, doi: 10.1144/0016-76492008-112.
- Gaina, C., Nasuti, A., Kimbell, G.S., and Blischke, A., 2017b, Break-up and seafloor spreading domains in the NE Atlantic: *Geological Society of London Special Publications*, v. 447, no. 1, p. SP447.12, doi: 10.1144/SP447.12.
- Gaina, C., Torsvik, T.H., van Hinsbergen, D.J.J., Medvedev, S., Werner, S.C., and Labails, C., 2013, The African plate: A history of oceanic crust accretion and subduction since the Jurassic: *Tectonophysics*, v. 604, p. 4–25, doi: 10.1016/j.tecto.2013.05.037.
- Le Gall, B., Tshoso, G., Dymant, J., Basira Kampunzu, A., Jourdan, F., Féraud, G., Bertrand, H., Aubourg, C., and Vétel, W., 2005, The Okavango giant mafic dyke swarm (NE Botswana): its structural significance within the Karoo Large Igneous Province: *Journal of Structural Geology*, v. 27, no. 12, p. 2234–2255, doi: <https://doi.org/10.1016/j.jsg.2005.07.004>.
- Gee, D.G., Fossen, H., Henriksen, N., and Higgins, A.K., 2008, From the early Paleozoic platforms of Baltica and Laurentia to the Caledonide orogen of Scandinavia and Greenland, *in* *Episodes*, *Episodes*, p. 44–51.
- Geiger, M., Clark, D.N., and Mette, W., 2004, Reappraisal of the timing of the breakup of Gondwana based on sedimentological and seismic evidence from the Morondava Basin, Madagascar: *Journal of African Earth Sciences*, v. 38, no. 4, p. 363–381, doi: 10.1016/j.jafrearsci.2004.02.003.
- Geoffroy, L., 2005, Volcanic passive margins: *Comptes Rendus - Geoscience*, v. 337, no. 16, p. 1395–1408, doi: 10.1016/j.crte.2005.10.006.
- Geoffroy, L., Callot, J.-P., Scaillet, S., Skuce, A., Gélard, J.P., Ravilly, M., Angelier, J., Bonin, B., Cayet, C., and Perrot, K., 2001, Southeast Baffin volcanic margin and the North American-Greenland plate separation: *Tectonics*, v. 20, no. 4, p. 566–584.
- Gerlings, J., Funck, T., Jackson, H.R., Loudon, K.E., and Klingelhofer, F., 2009, Seismic evidence for plume-derived volcanism during formation of the continental margin in southern Davis Strait and northern Labrador Sea: *Geophysical Journal International*, v. 176, no. 3, p. 980–994, doi: 10.1111/j.1365-246X.2008.04021.x.
- Gernigon, L., Blischke, A., Nasuti, A., and Sand, M., 2015, Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: Insights from new high-resolution aeromagnetic surveys in the Norway Basin: *Tectonics*, , no. July, p. 907–933, doi: 10.1002/2014TC003717.
- Gernigon, L., Brønner, M., Dumais, M.A., Gradmann, S., Grønlie, A., Nasuti, A., and Roberts, D., 2018, Basement inheritance and salt structures in the SE Barents Sea: Insights from new potential field data: *Journal of Geodynamics*, v. 119, no. March, p. 82–106, doi: 10.1016/j.jog.2018.03.008.
- Gill, R.C.O., Holm, P.M., and Nielsen, T.F.D., 1995, Was a short-lived Baffin Bay plume active prior to initiation of the present Icelandic plume? Clues from the high-Mg picrites of West Greenland: *Lithos*, v. 34, no. 1–3, p. 27–39, doi: 10.1016/0024-4937(95)90007-

1.

- Gill, R.C.O., Pedersen, A.K., and Larsen, J.G., 1992, Tertiary picrites in West Greenland: melting at the periphery of a plume? Geological Society, London, Special Publications, v. 68, no. 1, p. 335–348, doi: 10.1144/GSL.SP.1992.068.01.21.
- Gion, A., Williams, S., and Muller, D., 2017, A reconstruction of the Eurekan Orogeny incorporating deformation constraints: Tectonics, p. 304–320, doi: 10.1002/2015TC004094.
- Gladchenko, T.P., Hinz, K., Eldholm, O., Meyer, H., Neben, S., and Skogseid, J., 1997, South Atlantic volcanic margins: Journal of the Geological Society, v. 154, no. Gladchenko 1994, p. 465–470, doi: 10.1144/gsjgs.154.3.0465.
- Gladchenko, T.P., Skogseid, J., and Eldhom, O., 1998, Namibia volcanic margin: Marine Geophysical Researches, v. 20, no. 4, p. 313–341, doi: 10.1023/A:1004746101320.
- Glen, J.M.G., Renne, P.R., Milner, S.C., and Coe, R.S., 1997, Magma flow inferred from anisotropy of magnetic susceptibility in the coastal Paraná-Etendeka igneous province: Evidence for rifting before flood volcanism: Geology, v. 25, no. 12, p. 1131–1134, doi: 10.1130/0091-7613(1997)025<1131:MFIFAO>2.3.CO;2.
- Golonka, J., Ross, M.I., and Scotese, C.R., 1994, Phanerozoic paleogeographic and paleoclimatic modeling maps.: Canadian Society of Petroleum Geologists, v. Memoir 17, p. 1–47.
- Graça, M.C., Kuszniir, N., and Gomes Stanton, N.S., 2019, Crustal thickness mapping of the central South Atlantic and the geodynamic development of the Rio Grande Rise and Walvis Ridge: Marine and Petroleum Geology, v. 101, no. August 2018, p. 230–242, doi: 10.1016/j.marpetgeo.2018.12.011.
- Granot, R., and Dymant, J., 2015, The Cretaceous opening of the South Atlantic Ocean: Earth and Planetary Science Letters, v. 414, p. 156–163, doi: 10.1016/j.epsl.2015.01.015.
- Grocott, J., and McCaffrey, K., 2017, Basin Evolution and Destruction in an Early Proterozoic Continental Margin: the Rinkian Fold-Thrust Belt of Central West Greenland: Journal of the Geological Society, doi: 10.1144/jgs2016-109.
- Hall, S.A., Bird, D.E., McLean, D.J., Towle, P.J., Grant, J. V, and Danque, H.A., 2018, New constraints on the age of the opening of the South Atlantic basin: Marine and Petroleum Geology, v. 95, p. 50–66.
- Hames, W.E., Renne, P.R., and Ruppel, C., 2000, New evidence for geologically instantaneous emplacement of earliest Jurassic Central Atlantic magmatic province basalts on the North American margin: Geology, v. 28, no. 9, p. 859–862, doi: 10.1130/0091-7613(2000)28<859:NEFGIE>2.0.CO;2.
- Hankel, O., 1994, Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar: Geologische Rundschau, v. 83, no. 4, p. 703–710, doi: 10.1007/BF00251069.
- Hansen, J., Jerram, D.A., McCaffrey, K., and Passey, S.R., 2009, The onset of the North

- Atlantic Igneous Province in a rifting perspective: *Geological Magazine*, v. 146, no. 03, p. 309, doi: 10.1017/S0016756809006347.
- Hart, S.R., and Blusztajn, J., 2006, Age and geochemistry of the mafic sills, ODP site 1276, Newfoundland margin: *Chemical Geology*, v. 235, no. 3–4, p. 222–237, doi: 10.1016/j.chemgeo.2006.07.001.
- Hastie, W.W., Watkeys, M.K., and Aubourg, C., 2014, Magma flow in dyke swarms of the Karoo LIP: Implications for the mantle plume hypothesis: *Gondwana Research*, v. 25, no. 2, p. 736–755, doi: <https://doi.org/10.1016/j.gr.2013.08.010>.
- Hawkesworth, C., Kelley, S., Turner, S., Le Roex, A., and Storey, B., 1999, Mantle processes during Gondwana break-up and dispersal: *Journal of African Earth Sciences*, v. 28, no. 1, p. 239–261, doi: [https://doi.org/10.1016/S0899-5362\(99\)00026-3](https://doi.org/10.1016/S0899-5362(99)00026-3).
- Heeremans, M., Timmerman, M.J., Kirstein, L.A., and Faleide, J.I., 2004, New constraints on the timing of late Carboniferous-early Permian volcanism in the central North Sea: *Geological Society, London, Special Publications*, v. 223, no. 1, p. 177–193.
- Heine, C., Zoethout, J., and Müller, R.D., 2013, Kinematics of the South Atlantic rift: *Solid Earth*, v. 4, no. 2, p. 215–253, doi: 10.5194/se-4-215-2013.
- Helwig, J., Aronson, J., and Day, D.S., 1974, A late Jurassic mafic pluton in Newfoundland: *Canadian Journal of Earth Sciences*, , no. 11, p. 1314–1319, doi: 10.1139/e74-123.
- Heron, P.J., 2018, Mantle plumes and mantle dynamics in the Wilson cycle: *Geological Society, London, Special Publications*, , no. November, p. SP470.18, doi: 10.1144/SP470.18.
- Heron, P.J., and Lowman, J.P., 2014, The impact of Rayleigh number on assessing the significance of supercontinent insulation: *Journal of Geophysical Research: Solid Earth*, , no. 2008, p. 1–23, doi: 10.1002/2013JB010484.Received.
- Heron, P.J., and Lowman, J.P., 2010, Thermal response of the mantle following the formation of a super-plate: *Geophysical Research Letters*, v. 37, no. 22, p. 2–5, doi: 10.1029/2010GL045136.
- Heron, P.J., Pysklywec, R.N., and Stephenson, R., 2015, Intraplate orogenesis within accreted and scarred lithosphere: Example of the Eureka Orogeny, Ellesmere Island: *Tectonophysics*, v. 664, p. 202–213, doi: 10.1016/j.tecto.2015.09.011.
- Hinz, K., Neben, S., Gouseva, Y.B., and Kudryavtsev, G.A., 2004, A Compilation of Geophysical Data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica: *Marine Geophysical Researches*, v. 25, no. 3, p. 233–245, doi: 10.1007/s11001-005-1319-y.
- Hinz, K., Neben, S., Schreckenberger, B., Roeser, H.A., Block, M., Souza, K.G. De, and Meyer, H., 1999, The Argentine continental margin north of 48°S: Sedimentary successions, volcanic activity during breakup: *Marine and Petroleum Geology*, v. 16, no. 1, p. 1–25, doi: 10.1016/S0264-8172(98)00060-9.
- Hitchen, K., 2004, The geology of the UK Hatton-Rockall margin: *Marine and Petroleum Geology*, v. 21, no. 8, p. 993–1012, doi: 10.1016/j.marpetgeo.2004.05.004.

- Hitchen, K., Stoker, M.S., Evans, D., and Beddoe-Stephens, B., 1995, Permo-Triassic sedimentary and volcanic rocks in basins to the north and west of Scotland: Geological Society, London, Special Publications, v. 91, no. 1, p. 87 LP-102.
- Hodych, J.P., and Hayatsu, A., 1980, K-Ar isochron age and paleomagnetism of diabase along the trans-Avalon aeromagnetic lineament - evidence of Late Triassic rifting in Newfoundland: Canadian Journal of Earth Sciences, v. 17, doi: 10.1139/e80-045.
- Holbrook, W.S., and Kelemen, P.B., 1993, Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup: Nature, v. 364, no. 6436, p. 433–436, doi: 10.1038/364433a0.
- Holbrook, W.S., Larsen, H.C., Korenaga, J., Dahl-Jensen, T., Reid, I.D., Kelemen, P.B., Hopper, J.R., Kent, G.M., Lizarralde, D., Bernstein, S., and Detrick, R.S., 2001, Mantle thermal structure and active upwelling during continental breakup in the North Atlantic: Earth and Planetary Science Letters, v. 190, no. 3, p. 251–266, doi: 10.1016/S0012-821X(01)00392-2.
- Holdsworth, R.E., Handa, M., Miller, J.A., and Buick, I.S., 2001, Continental reactivation and reworking: an introduction: Geological Society, London, Special Publications, v. 184, no. 1, p. 1–12, doi: 10.1144/gsl.sp.2001.184.01.01.
- Hole, M., and Natland, J.H. Magmatism in the North Atlantic Igneous Province; mantle temperatures, rifting and geodynamics: Earth-Science Reviews,.
- Hosseinpour, M., Müller, R.D., Williams, S.E., and Whittaker, J.M., 2013, Full-fit reconstruction of the Labrador Sea and Baffin Bay: Solid Earth, v. 4, no. 2, p. 461–479, doi: 10.5194/se-4-461-2013.
- Huisman, R.S., Podladchikov, Y.Y., and Cloetingh, S., 2001, Transition from passive to active rifting: Relative importance of asthenospheric doming and passive extension of the lithosphere.: Journal of Geophysical Research, v. 106, no. B6, p. 11,271-11291.
- Hunegnaw, A., Sage, L., and Gonnard, R., 2007, Hydrocarbon Potential of teh intracratonic Ogaden Basin, SE Ethiopia: Journal of Petroleum Geology, v. 21, no. 4, p. 401–425, doi: 10.1111/j.1747-5457.1998.tb00793.x.
- Jackson, H.R., Keen, C.E., Falconer, R.K.H., and Appleton, K.P., 1979, New geophysical evidence for sea-floor spreading in central Baffin Bay: Canadian Journal of Earth Sciences, v. 16, p. 2122–2135, doi: 10.1139/e79-200.
- Jokat, W., 2003, Seismic investigations along the western sector of Alpha Ridge, Central Arctic Ocean: Geophysical Journal International, v. 152, no. 1, p. 185–201, doi: 10.1046/j.1365-246X.2003.01839.x.
- Jokat, W., Boebel, T., König, M., and Meyer, U., 2003, Timing and geometry of early Gondwana breakup: Journal of Geophysical Research: Solid Earth, v. 108, no. B9.
- Jones, M.T., Augland, L.E., Shephard, G.E., Burgess, S.D., Eliassen, G.T., Jochmann, M.M., Friis, B., Jerram, D.A., Planke, S., and Svensen, H.H., 2017, Constraining shifts in North Atlantic plate motions during the Palaeocene by U-Pb dating of Svalbard tephra layers: Scientific Reports, v. 7, no. 1, p. 6822.

- Jones, E.J.W., Ramsay, A.T.S., Preston, N.J., and Smith, A.C.S., 1974, A Cretaceous guyot in the Rockall Trough: *Nature*, v. 251, no. 5471, p. 129.
- Jourdan, F., Bertrand, H., Féraud, G., Le Gall, B., and Watkeys, M.K., 2009, Lithospheric mantle evolution monitored by overlapping large igneous provinces: Case study in southern Africa: *Lithos*, v. 107, no. 3, p. 257–268, doi: <https://doi.org/10.1016/j.lithos.2008.10.011>.
- Jourdan, F., Féraud, G., Bernard, H., Kampunzu, A.B., Tshoso, G., Watkeys, M. K., and Le Gall, B., 2007a, The Karoo large igneous province: Brevity, origin, and relation with mass extinction questioned by new 40 Ar / 39 Ar age data : REPLY: *Geology: Forum*, v. 1, p. 2000–2002, doi: 10.1130/G23593Y.1.
- Jourdan, F., Féraud, G., Bertrand, H., Kampunzu, A.B., Tshoso, G., Watkeys, M.K., and Le Gall, B., 2005, Karoo large igneous province: Brevity, origin, and relation to mass extinction questioned by new 40Ar/39Ar age data: *Geology*, v. 33, no. 9, p. 745–748, doi: 10.1130/G21632.1.
- Jourdan, F., Féraud, G., Bertrand, H., and Watkeys, M.K., 2007b, From flood basalts to the inception of oceanization: Example from the 40Ar/39Ar high- resolution picture of the Karoo large igneous province: *Geochemistry, Geophysics, Geosystems*, v. 8, no. 2, doi: 10.1029/2006GC001392.
- Julian, B., Foulger, G., Hatfield, O., Jackson, S., Simpson, E., Einbeck, J., and Moore, A., 2015, Hotspots in hindsight: The Geological Society of America Special Paper, v. 514, p. 105–121.
- Jung, W., and Vogt, P.R., 1997, A gravity and magnetic anomaly study of the extinct Aegir Ridge, Norwegian Sea: *Journal of Geophysical Research: Solid Earth*, v. 102, no. B3, p. 5065–5089.
- Karner, G.D., and Shillington, D.J., 2005, Basalt sills of the U reflector, Newfoundland basin: A serendipitous dating technique: *Geology*, v. 33, no. 12, p. 985–988, doi: 10.1130/G21971.1.
- Kassim, M.A., Carnignani, L., Conti, P., and Fantozzi, P.L., 2002, Geology of the Mesozoic-Tertiary sedimentary basins in southwestern Somalia: *Journal of African Earth Sciences*, v. 34, no. 1, p. 3–20, doi: [https://doi.org/10.1016/S0899-5362\(01\)00102-6](https://doi.org/10.1016/S0899-5362(01)00102-6).
- Kearey, P., Klepeis, K., and Vine, F., 2009, *Global Tectonics*: Wiley-Blackwell.
- Keeley, M.L., and Light, M.P.R., 1993, Basin evolution and prospectivity of the Argentine continental margin.: *Journal of Petroleum Geology*, v. 16, no. 4, p. 451–464.
- Keen, C.E., Dafoe, L.T., and Dickie, K., 2014, A volcanic province near the Western termination of the Charlie-Gibbs Fracture Zone at the rifted margin, offshore northeast Newfoundland: *Tectonics*, v. 33, no. 6, p. 1133–1153, doi: 10.1002/2014TC003547.
- Keen, C.E., Dickie, K., and Dafoe, L.T., 2017, Structural characteristics of the ocean-continent transition along the rifted continental margin, offshore central Labrador: *Marine and Petroleum Geology*, doi: 10.1016/j.marpetgeo.2017.10.012.

- Keen, C.E., Dickie, K., and Dehler, S.A., 2012, The volcanic margins of the northern Labrador Sea: Insights to the rifting process: *Tectonics*, v. 31, no. 1, p. 1–13, doi: 10.1029/2011TC002985.
- Kelemen, P.B., and Holbrook, W.S., 1995, Origin of thick, high-velocity igneous crust along the U.S. East Coast Margin: *Journal of Geophysical Research: Solid Earth*, v. 100, no. B6, p. 10077–10094, doi: 10.1029/95JB00924.
- Keppie, F., 2016, How subduction broke up Pangaea with implications for the supercontinent cycle: Geological Society, London, Special Publications, v. 424, no. 1, p. 265–288, doi: 10.1144/SP424.8.
- Kerr, A., Ryan, B., Gower, C.F., and Wardle, R.J., 1996, The Makkovik Province: extension of the Ketilidian Mobile Belt in mainland North America: Geological Society, London, Special Publications, v. 112, no. 1, p. 155–177, doi: 10.1144/GSL.SP.1996.112.01.09.
- King, S.D., and Anderson, D.L., 1995, An alternative mechanism of flood basalt formation: *Earth and Planetary Science Letters*, v. 136, no. 3–4, p. 269–279, doi: 10.1016/0012-821X(95)00205-Q.
- King, S.D., and Anderson, D.L., 1998, Edge-driven convection: *Earth and Planetary Science Letters*, v. 160, no. 3–4, p. 289–296, doi: 10.1016/S0012-821X(98)00089-2.
- King, A.F., and McMillan, N.J., 1975, A Mid-Mesozoic Breccia from the Coast of Labrador: *Canadian Journal of Earth Sciences*, v. 12, no. 1, p. 44–51, doi: 10.1139/e75-005.
- Klausen, M.B., 2009, The Lebombo monocline and associated feeder dyke swarm: Diagnostic of a successful and highly volcanic rifted margin? *Tectonophysics*, v. 468, no. 1, p. 42–62, doi: <https://doi.org/10.1016/j.tecto.2008.10.012>.
- Klimke, J., and Franke, D., 2016, Gondwana breakup: No evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya: *Terra Nova*, p. n/a–n/a, doi: 10.1111/ter.12214.
- Klimke, J., Franke, D., Mahanjane, E.S., and Leitchenkov, G., 2018, Tie points for Gondwana reconstructions from a structural interpretation of the Mozambique Basin, East Africa and the Riiser-Larsen Sea, Antarctica: *Solid Earth*, v. 9, no. 1, p. 25–37, doi: 10.5194/se-9-25-2018.
- Klitgord, K.D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, in Vogt, P.R. and Tucholke, B.E. eds., *The Western North Atlantic Region, Geology of North America*, p. 351–378.
- Knesel, K.M., Souza, Z.S., Vasconcelos, P.M., Cohen, B.E., and Silveira, F. V., 2011, Young volcanism in the Borborema Province, NE Brazil, shows no evidence for a trace of the Fernando de Noronha plume on the continent: *Earth and Planetary Science Letters*, v. 302, no. 1, p. 38–50.
- Konrad, K., Koppers, A.A.P., Steinberger, B., Finlayson, V.A., Konter, J.G., and Jackson, M.G., 2018, On the relative motions of long-lived Pacific mantle plumes: *Nature communications*, v. 9, no. 1, p. 854.

- Kontak, D.J., 2008, On the edge of CAMP: Geology and volcanology of the Jurassic North Mountain Basalt, Nova Scotia: *Lithos*, v. 101, no. 1–2, p. 74–101, doi: 10.1016/j.lithos.2007.07.013.
- Koopmann, H., Brune, S., Franke, D., and Breuer, S., 2014a, Linking rift propagation barriers to excess magmatism at volcanic rifted margins: *Geology*, v. 42, no. 12, p. 1071–1074, doi: 10.1130/G36085.1.
- Koopmann, H., Franke, D., Schreckenberger, B., Schulz, H., Hartwig, A., Stollhofen, H., and di Primio, R., 2014b, Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data: *Marine and Petroleum Geology*, v. 50, p. 22–39, doi: 10.1016/j.marpetgeo.2013.10.016.
- Koopmann, H., Schreckenberger, B., Franke, D., Becker, K., and Schnabel, M., 2016, The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust: *Geological Society, London, Special Publications*, v. 420, no. 1, p. 315–340, doi: 10.1144/SP420.2.
- Korenaga, J., 2004, Mantle mixing and continental breakup magmatism: *Earth and Planetary Science Letters*, v. 218, no. 3–4, p. 463–473, doi: 10.1016/S0012-821X(03)00674-5.
- Korenaga, J., and Kelemen, P.B., 2000, Major element heterogeneity in the mantle source of the North Atlantic igneous province: *Earth and Planetary Science Letters*, v. 184, no. 1, p. 251–268.
- Kravchinsky, V.A., Cogné, J.-P., Harbert, W.P., and Kuzmin, M.I., 2002, Evolution of the Mongol-Okhotsk Ocean as constrained by new palaeomagnetic data from the Mongol-Okhotsk suture zone, Siberia: *Geophysical Journal International*, v. 148, no. 1, p. 34–57.
- Labails, C., Olivet, J.L., Aslanian, D., and Roest, W.R., 2010, An alternative early opening scenario for the Central Atlantic Ocean: *Earth and Planetary Science Letters*, v. 297, no. 3–4, p. 355–368, doi: 10.1016/j.epsl.2010.06.024.
- Langmuir, C., 2013, Mantle geodynamics: Older and hotter: *Nature Geoscience*, v. 6, no. 5, p. 332.
- Larsen, L.M., Heaman, L.M., Creaser, R.A., Duncan, R.A., Frei, R., and Hutchison, M., 2009, Tectonomagmatic events during stretching and basin formation in the Labrador Sea and the Davis Strait: evidence from age and composition of Mesozoic to Palaeogene dyke swarms in West Greenland: *Journal of the Geological Society*, v. 166, no. 6, p. 999–1012, doi: 10.1144/0016-76492009-038.
- Larsen, L.M., Pedersen, A.K., Tegner, C., Duncan, R.A., Hald, N., and Larsen, J.G., 2016, Age of Tertiary volcanic rocks on the West Greenland continental margin: volcanic evolution and event correlation to other parts of the North Atlantic Igneous Province: *Geological Magazine*, v. 153, no. 03, p. 487–511, doi: 10.1017/S0016756815000515.
- Larsen, H.C., and Saunders, A.D., 1998, Tectonism and volcanism at the southeast Greenland rifted margin: a record of plume impact and later continental rupture: *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 152, doi: 10.2973/odp.proc.sr.152.1998.

- Laske, G., Masters, G., Ma, Z., and Pasyanos, M.E., 2013, CRUST1.0: An Updated Global Model of Earth's Crust: *Geophys. Res. Abstracts*, v. 15, p. Abstract EGU2013--2658.
- Lawver, L.A., Gahagan, L.M., and Dalziel, I.W.D., 1998, A tight fit-early Mesozoic Gondwana, a plate reconstruction perspective: *Memoires of the National Institute of Polar Research*, , no. 53, p. 214–229.
- Lawver, L.A., and Müller, R.D., 1994, Iceland hotspot track: *Geology*, v. 22, no. 4, p. 311–314, doi: 10.1130/0091-7613(1994)022<0311:IHT>2.3.CO;2.
- Leinweber, V.T., and Jokat, W., 2012, The Jurassic history of the Africa–Antarctica corridor — new constraints from magnetic data on the conjugate continental margins: *Tectonophysics*, v. 530–531, p. 87–101, doi: <https://doi.org/10.1016/j.tecto.2011.11.008>.
- Leitchenkov, G., Guseva, J., Gandyukhin, V., Grikurov, G., Kristoffersen, Y., Sand, M., Golynsky, A., and Aleshkova, N., 2008, Crustal structure and tectonic provinces of the Riiser-Larsen Sea area (East Antarctica): results of geophysical studies: *Marine Geophysical Researches*, v. 29, no. 2, p. 135–158.
- Leleu, S., Hartley, A.J., van Oosterhout, C., Kennan, L., Ruckwied, K., and Gerdes, K., 2016, Structural, stratigraphic and sedimentological characterisation of a wide rift system: the Triassic rift system of the Central Atlantic Domain: *Earth-Science Reviews*, v. 158, p. 89–124.
- Leslie, A.G., Smith, M., and Soper, N.J., 2008, Laurentian margin evolution and the Caledonian orogeny— A template for Scotland and East Greenland: *The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia*, v. 202, no. 202, p. 307–343, doi: 10.1130/2008.1202(06).
- Li, Z.-X., Bogdanova, S. V, Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., and Jacobs, J., 2008, Assembly, configuration, and break-up history of Rodinia: a synthesis: *Precambrian research*, v. 160, no. 1–2, p. 179–210.
- Ligi, M., Bonatti, E., Cipriani, A., and Ottolini, L., 2005, Water-rich basalts at mid-ocean-ridge cold spots: *Nature*, v. 434, no. 7029, p. 66–69, doi: 10.1038/nature03264.
- Lopes, R.P., and Ulbrich, M.N.C., 2015, Geochemistry of the alkaline volcanicsubvolcanic rocks of the Fernando de Noronha Archipelago, southern Atlantic Ocean: *Brazilian Journal of Geology*, v. 45, no. 2, p. 307–333.
- Lovecchio, J.P., Rohais, S., Joseph, P., Bolatti, N.D., Kress, P.R., Gerster, R., and Ramos, V.A., 2018, Multistage rifting evolution of the Colorado basin (offshore Argentina): Evidence for extensional settings prior to the South Atlantic opening: *Terra Nova*, v. 30, no. 5, p. 359–368.
- Lundin, E., 2002, North Atlantic – Arctic : Overview of sea-floor spreading and rifting history, *in* Mid Norway plate reconstructions atlas with global and Atlantic perspectives, p. 41–75.
- Lundin, E., and Doré, A., 2005a, Fixity of the Iceland ‘hotspot’ on the Mid-Atlantic Ridge: Observational evidence, mechanisms, and implications for Atlantic volcanic margins:

- Geological Society of America Special Papers, v. 2388, no. 36, p. 627–651, doi: 10.1130/2005.2388(36).
- Lundin, E.R., and Doré, A.G., 2005b, NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic–Arctic linkage, *in* Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference, p. 739–754.
- Lundin, E.R., and Doré, A.G., 2018, Non-Wilsonian break-up predisposed by transforms : examples from the North Atlantic and Arctic: Geological Society of London, Special Publications, v. 470, doi: 10.1144/SP470.6.
- Lundin, E.R., Doré, A.G., and Redfield, T.F., 2018, Magmatism and extension rates at rifted margins: Petroleum Geoscience, p. 32–33.
- Luttinen, A. V, 2018, Bilateral geochemical asymmetry in the Karoo large igneous province: Scientific reports, v. 8, no. 1, p. 5223.
- Macdonald, D., Gomez-Perez, I., Franzese, J., Spalletti, L., Lawver, L., Gahagan, L., Dalziel, I., Thomas, C., Trewin, N., Hole, M., and Paton, D., 2003, Mesozoic break-up of SW Gondwana: Implications for regional hydrocarbon potential of the southern South Atlantic: Marine and Petroleum Geology, v. 20, no. 3–4, p. 287–308, doi: 10.1016/S0264-8172(03)00045-X.
- Macgregor, D., 2018, History of the development of Permian–Cretaceous rifts in East Africa: a series of interpreted maps through time: Petroleum Geoscience, v. 24, no. 1, p. 8–20.
- Magee, C., Jackson, C.A.L., and Schofield, N., 2014, Diachronous sub-volcanic intrusion along deep-water margins: Insights from the Irish Rockall Basin: Basin Research, v. 26, no. 1, p. 85–105, doi: 10.1111/bre.12044.
- Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A.L., Bastow, I.D., Schofield, N., Stevenson, C.T.E., McLean, C., McCarthy, W., and Shtukert, O., 2016, Lateral magma flow in mafic sill complexes: Geosphere, v. 12, no. 3, p. GES01256.1, doi: 10.1130/GES01256.1.
- Mahanjane, E.S., 2012, A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development: Marine and Petroleum Geology, v. 36, no. 1, p. 1–12, doi: <https://doi.org/10.1016/j.marpetgeo.2012.05.007>.
- Maillard, A., Malod, J., Thiébot, E., Klingelhoefer, F., and Réhault, J.-P., 2006, Imaging a lithospheric detachment at the continent–ocean crustal transition off Morocco: Earth and Planetary Science Letters, v. 241, no. 3–4, p. 686–698.
- Malinverno, A., Hildebrandt, J., Tominaga, M., and Channell, J.E.T., 2012, M-sequence geomagnetic polarity time scale (MHTC12) that steadies global spreading rates and incorporates astrochronology constraints: Journal of Geophysical Research: Solid Earth, v. 117, no. 6, p. 1–17, doi: 10.1029/2012JB009260.
- Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., and De Min, A., 1999, Extensive 200-million year old continental flood basalts of the Central Atlantic

- Magmatic Province: *Science*, v. 284, no. April, p. 616–618.
- Maslanyj, M.P., Light, M.P.R., Greenwood, R.J., and Banks, N.L., 1992, Extension tectonics offshore Namibia and evidence for passive rifting in the South Atlantic: *Marine and Petroleum Geology*, v. 9, no. 6, p. 590–601, doi: 10.1016/0264-8172(92)90032-A.
- May, P.R., 1971, Pattern of Triassic-Jurassic Diabase Dikes around the North Atlantic in the Context of Predrift Position of the Continents: *GSA Bulletin*, v. 82, no. 5, p. 1285–1292.
- McBride, J.H., Nelson, K.D., and Brown, L.D., 1989, Evidence and implications of an extensive early Mesozoic rift basin and basalt/diabase sequence beneath the southeast Coastal Plain: *GSA Bulletin*, v. 101, no. 4, p. 512–520.
- McCann, T., Pascal, C., Timmerman, M.J., Krzywiec, P., López-Gómez, J., Wetzel, L., Krawczyk, C.M., Rieke, H., and Lamarche, J., 2006, Post-Variscan (end Carboniferous-Early Permian) basin evolution in Western and Central Europe: *Geological Society, London, Memoirs*, v. 32, no. 1, p. 355–388, doi: 10.1144/GSL.MEM.2006.032.01.22.
- McHone, J.G., 1996, Constraints on the mantle plume model for mesozoic alkaline intrusions in northeastern North America: *Canadian Mineralogist*, v. 34, no. 2, p. 325–334.
- McHone, J.G., 2000, Non-plume magmatism and rifting during the opening of the central Atlantic Ocean: *Tectonophysics*, v. 316, no. 3–4, p. 287–296, doi: 10.1016/S0040-1951(99)00260-7.
- McHone, J.G., 2003, Volatile Emissions from Central Atlantic Magmatic Province Basalts: Mass Assumptions and Environmental Consequences, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, American Geophysical Union, p. 241–254.
- McWhae, J.R.H., Elie, R., Laughton, K.C., and Gunther, P.R., 1980, Stratigraphy and Petroleum Prospects of the Labrador Shelf: *Bulletin of Canadian Petroleum Geology*, v. 28, no. 4, p. 460–488.
- Meier, T., Soomro, R.A., Viereck, L., Lebedev, S., Behrmann, J.H., Weidle, C., Cristiano, L., and Hanemann, R., 2016, Mesozoic and Cenozoic evolution of the Central European lithosphere: *Tectonophysics*, v. 692, p. 58–73.
- Melankholina, E.N., 2008, Tectonotype of volcanic passive margins in the Norwegian-Greenland region: *Geotectonics*, v. 42, no. 3, p. 225–244, doi: 10.1134/S0016852108030059.
- Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., 2002, Characteristics of volcanic rifted margins: *Geological Society of America Special Papers*, v. 362, p. 1–14, doi: 10.1130/0-8137-2362-0.1.
- Merdith, A.S., Williams, S.E., Sascha, B., Collins, A.S., and Muller, D., 2019, Rift and plate boundary evolution across two supercontinent cycles: *Global and Planetary Change*, v. 173, p. 1–14, doi: 10.1016/j.gloplacha.2018.11.006.
- Merle, O., 2011, A simple continental rift classification: *Tectonophysics*, v. 513, no. 1–4, p. 88–95, doi: 10.1016/j.tecto.2011.10.004.

- Merle, R., Marzoli, A., Reisberg, L., Bertrand, H., Nemchin, A., Chiaradia, M., Callegaro, S., Jourdan, F., Bellieni, G., Kontak, D., Puffer, J., and McHone, J.G., 2013, Sr, Nd, Pb and Os Isotope Systematics of CAMP Tholeiites from Eastern North America (ENA): Evidence of a Subduction-enriched Mantle Source: *Journal of Petrology*, v. 55, no. 1, p. 133–180.
- Meyer, R., Wijk, J. Van, and Gernigon, L., 2007, The North Atlantic Igneous Province: A review of models for its formation: *Geological Society of America, Special Paper Amer*, v. 430, no. 26, p. 525–552, doi: 10.1130/2007.2430(26).
- Mjelde, R., Breivik, A.J., Raum, T., Mittelstaedt, E., Ito, G., and Faleide, J.I.I., 2008, Magmatic and tectonic evolution of the North Atlantic: *Journal of the Geological Society*, v. 165, no. Sigmundsson 2006, p. 31–42, doi: 10.1144/0016-76492007-018.
- Mjelde, R., and Faleide, J.I., 2009, Variation of Icelandic and Hawaiian magmatism: Evidence for co-pulsation of mantle plumes? *Marine Geophysical Researches*, v. 30, no. 1, p. 61–72, doi: 10.1007/s11001-009-9066-0.
- Mohriak, W., Nemčok, M., and Enciso, G., 2008, South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil: *Geological Society, London, Special Publications*, v. 294, no. 1, p. 365 LP-398.
- Mohriak, W.U., Rosendahl, B.R., Turner, J.P., and Valente, S.C., 2002, Crustal architecture of South Atlantic volcanic margins: *Geological Society of America Special Papers*, v. 362, p. 159–202, doi: 10.1130/0-8137-2362-0.159.
- Mordret, A., 2018, Uncovering the Iceland hotspot track beneath Greenland: *Journal of Geophysical Research: Solid Earth*,.
- Morgan, W.J., 1971, Convection plumes in the lower mantle: *Nature*, v. 2310, p. 42–43, doi: 10.1038/230042a0.
- Morgan, J.W., 1983, Hotspot tracks and the early rifting of the Atlantic: *Tectonophysics*, v. 94, no. 1, p. 123–139, doi: [https://doi.org/10.1016/0040-1951\(83\)90013-6](https://doi.org/10.1016/0040-1951(83)90013-6).
- Morgan, W.J., 1981, Hotspot tracks and the opening of the Atlantic and Indian Oceans. (C. Emilian, Ed.): Wiley-Interscience.
- Morgan, W.J., and Morgan, J.P., 2007, Plate velocities in the hotspot reference frame: *Special Paper - Geological Society of America*, v. 430, p. 65.
- Morton, A.C., Hitchen, K., Ritchie, J.D., Hine, N.M., Whitehouse, M., and Carter, S.G., 1995, Late Cretaceous basalts from Rosemary Bank, Northern Rockall Trough: *Journal of the Geological Society*, v. 152, no. 6, p. 947 LP-952.
- Mosar, J., Lewis, G., and Torsvik, T., 2002, North Atlantic sea-floor spreading rates: implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea: *Journal of the Geological Society*, v. 159, no. 5, p. 503–515, doi: 10.1144/0016-764901-093.
- Moulin, M., Aslanian, D., Rabineau, M., Patriat, M., and Matias, L., 2013, Kinematic keys of the Santos–Namibe basins: *Geological Society, London, Special Publications*, v. 369,

- no. 1, p. 91–107, doi: 10.1144/SP369.3.
- Moulin, M., Aslanian, D., and Unternehr, P., 2009, A new starting point for the South and Equatorial Atlantic Ocean: *Earth-Science Reviews*, v. 97, no. 1–4, p. 59–95.
- Mueller, C.O., and Jokat, W., 2017, Geophysical evidence for the crustal variation and distribution of magmatism along the central coast of Mozambique: *Tectonophysics*, v. 712–713, p. 684–703, doi: <https://doi.org/10.1016/j.tecto.2017.06.007>.
- Müller, R.D., Gaina, C., Roest, W.R., and Hansen, D.L., 2001, A recipe for microcontinent formation: *Geology*, v. 29, no. 3, p. 203–206, doi: 10.1130/0091-7613(2001)029<0203:ARFMF>2.0.CO;2.
- Murphy, J.B., and Nance, R.D., 2013, Speculations on the mechanisms for the formation and breakup of supercontinents: *Geoscience Frontiers*, v. 4, no. 2, p. 185–194, doi: 10.1016/j.gsf.2012.07.005.
- Nance, R.D., Murphy, J.B., and Santosh, M., 2014, The supercontinent cycle: A retrospective essay: *Gondwana Research*, v. 25, no. 1, p. 4–29, doi: 10.1016/j.gr.2012.12.026.
- Nelson, C.E., Jerram, D.A., Clayburn, J.A.P., Halton, A.M., and Roberge, J., 2015, Eocene volcanism in offshore southern Baffin Bay: *Marine and Petroleum Geology*, v. 67, p. 678–691, doi: 10.1016/j.marpetgeo.2015.06.002.
- Nguyen, L.C., Hall, S.A., Bird, D.E., and Ball, P.J., 2016, Reconstruction of the East Africa and Antarctica continental margins: *Journal of Geophysical Research: Solid Earth*, v. 121, no. 6, p. 4156–4179.
- Nielsen, S.B.S.B., Stephenson, R.A., and Schiffer, C., 2014, Deep controls on intraplate basin inversion, *in* Talwani, P. ed., *Intraplate Earthquakes*, Cambridge University Press, p. 257–274.
- Nielsen, S.B., Stephenson, R., and Thomsen, E., 2007, Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations.: *Nature*, v. 450, no. 7172, p. 1071–1074, doi: 10.1038/nature06379.
- Nirrengarten, M., Manatschal, G., Tugend, J., Kuszniir, N., and Sauter, D., 2018, Kinematic evolution of the southern North Atlantic: implications for the formation of hyper-extended rift systems: *Tectonics*, p. 2, doi: 10.1002/2017TC004495.
- Nomade, S., Knight, K.B., Beutel, E., Renne, P.R., Verati, C., Féraud, G., Marzoli, A., Youbi, N., and Bertrand, H., 2007, Chronology of the Central Atlantic Magmatic Province: Implications for the Central Atlantic rifting processes and the Triassic-Jurassic biotic crisis: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 244, no. 1–4, p. 326–344, doi: 10.1016/j.palaeo.2006.06.034.
- O'Connor, J.M., and Jokat, W., 2015, Tracking the Tristan-Gough mantle plume using discrete chains of intraplate volcanic centers buried in the Walvis Ridge: *Geology*, v. 43, no. 8, p. 715–718.
- O'Neill, C., Müller, D., and Steinberger, B., 2005, On the uncertainties in hot spot reconstructions and the significance of moving hot spot reference frames: *Geochemistry*,

Geophysics, Geosystems, v. 6, no. 4.

- Oakey, G.N., and Chalmers, J. a, 2012, A new model for the Paleogene motion of Greenland relative to North America : Plate reconstructions of the Davis Strait and Nares Strait regions between Canada and Greenland: *Journal of Geophysical Research: Solid Earth*, v. 117, no. B10, p. 1–28, doi: 10.1029/2011JB008942.
- Olierook, H.K.H., Jiang, Q., Jourdan, F., and Chiaradia, M., 2019, Greater Kerguelen large igneous province reveals no role for Kerguelen mantle plume in the continental breakup of eastern Gondwana: *Earth and Planetary Science Letters*, v. 511, p. 244–255.
- Olsen, P.E., 1997, Stratigraphic Record of the Early Mesozoic Breakup of Pangea in the Laurasia-Gondwana Rift System: *Annual Review of Earth and Planetary Sciences*, v. 25, no. 1, p. 337–401, doi: 10.1146/annurev.earth.25.1.337.
- Olsen, P.E., Kent, D. V, Et-Touhami, M., and Puffer, J., 2003, Cyclo-, Magneto-, and Bio-Stratigraphic Constraints on the Duration of the Camp Event and its Relationship to the Triassic-Jurassic Boundary, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, American Geophysical Union, p. 7–32.
- Panfili, G., Cirilli, S., Dal Corso, J., Bertrand, H., Medina, F., Youbi, N., and Marzoli, A., 2019, New biostratigraphic constraints show rapid emplacement of the Central Atlantic Magmatic Province (CAMP) during the end-Triassic mass extinction interval: *Global and planetary change*, v. 172, p. 60–68.
- Papezik, V.S., and Hodych, J.P., 1980, Early Mesozoic diabase dikes of the Avalon Peninsula, Newfoundland; petrochemistry, mineralogy, and origin: *Canadian Journal of Earth Sciences*, v. 17, no. 10, p. 1417–1430, doi: 10.1139/e80-149.
- Papini, M., and Benvenuti, M., 2008, The Toarcian–Bathonian succession of the Antsiranana Basin (NW Madagascar): Facies analysis and tectono-sedimentary history in the development of the East Africa-Madagascar conjugate margins: *Journal of African Earth Sciences*, v. 51, no. 1, p. 21–38, doi: <https://doi.org/10.1016/j.jafrearsci.2007.11.003>.
- Paton, D.A., Mortimer, E.J., Hodgson, N., and van der Spuy, D., 2016, The missing piece of the South Atlantic jigsaw: when continental break-up ignores crustal heterogeneity: Geological Society, London, Special Publications, v. 438, doi: 10.1144/SP438.8.
- Pe-Piper, G., Jansa, L.F., and Lambert, R.S.J., 1992, Early Mesozoic magmatism on the eastern Canadian margin: Petrogenetic and tectonic significance: *Geological Society of America Special Paper*, v. 268, no. 2.
- Pe-Piper, G., Mereddyk, S., Zhang, Y., Piper, D.J.W., and Edinger, E., 2013, Petrology and tectonic significance of seamounts within transitional crust east of Orphan Knoll, offshore eastern Canada: *Geo-Marine Letters*, v. 33, no. 6, p. 433–447, doi: 10.1007/s00367-013-0342-2.
- Peace, A.L.L., Dempsey, E.D.D., Schiffer, C., Welford, J.K., McCaffrey, K., Imber, J., and Phethean, J., 2018a, Evidence for Basement Reactivation during the Opening of the Labrador Sea from the Makkovik Province, Labrador, Canada: Insights from Field Data and Numerical Models: *Geosciences*, v. 8, no. 8, p. 308, doi: 10.3390/geosciences8080308.

- Peace, A.L., Foulger, G.R., Schiffer, C., and McCaffrey, K.J.W., 2017a, Evolution of Labrador Sea–Baffin Bay: Plate or Plume Processes? *Geoscience Canada*, v. 44, no. 3, doi: 10.12789/geocanj.2017.44.120.
- Peace, A.L., McCaffrey, K.J.W., Imber, J., Hobbs, R., van Hunen, J., and Gerdes, K., 2017b, Quantifying the influence of sill intrusion on the thermal evolution of organic-rich sedimentary rocks in nonvolcanic passive margins: An example from ODP 210-1276, offshore Newfoundland, Canada: *Basin Research*, v. 29, no. 3, p. 249–265, doi: 10.1111/bre.12131.
- Peace, A., McCaffrey, K.J.W., Imber, J., van Hunen, J., Hobbs, R., and Wilson, R., 2018b, The role of pre-existing structures during rifting, continental breakup and transform system development, offshore West Greenland: *Basin Research*, v. 30, no. 3, p. 373–394, doi: 10.1111/bre.12257.
- Peace, A., McCaffrey, K.J.W., Imber, J., Phethean, J., Nowell, G., Gerdes, K., and Dempsey, E., 2016, An evaluation of Mesozoic rift-related magmatism on the margins of the Labrador Sea: Implications for rifting and passive margin asymmetry: *Geosphere*, v. 12, no. 6, doi: 10.1130/GES01341.1.
- Peace, A.L., Welford, J.K., Geng, M., Sandeman, H., Gaetz, B.D., and Ryan, S.S., 2018c, Rift-related magmatism on magma-poor margins: Structural and potential-field analyses of the Mesozoic Notre Dame Bay intrusions, Newfoundland, Canada and their link to North Atlantic Opening: *Tectonophysics*, v. 745, no. October, p. 24–45, doi: 10.1016/j.tecto.2018.07.025.
- Peace, A.L., Welford, J.K., Geng, M., Sandeman, H., Gaetz, B.D., and Ryan, S.S., 2018d, Structural geology data and 3-D subsurface models of the Budgell Harbour Stock and associated dykes, Newfoundland, Canada: *Data in Brief*, p. 1–7, doi: 10.1016/j.dib.2018.10.072.
- Peate, D.W., 1997, The Paraná-Etendeka Province: In: J.J. Mahoney and M.F. Coffin (Editors), *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, p. 217–245.
- Pegram, W.J., 1990, Development of continental lithospheric mantle as reflected in the chemistry of the Mesozoic Appalachian Tholeiites, U.S.A.: *Earth and Planetary Science Letters*, v. 97, no. 3, p. 316–331, doi: [https://doi.org/10.1016/0012-821X\(90\)90049-4](https://doi.org/10.1016/0012-821X(90)90049-4).
- Péron-Pinvidic, G., Hopper, J.R., Stoker, M., Gaina, C., Funck, T., Ártíng, U.E., and Doornenbal, J.C., 2017, The NE Atlantic region: a reappraisal of crustal structure, tectonostratigraphy and magmatic evolution – an introduction to the NAG-TEC project: Geological Society, London, Special Publications, p. SP447.17, doi: 10.1144/SP447.17.
- Petersen, K.D., and Schiffer, C., 2016, Wilson cycle passive margins: Control of orogenic inheritance on continental breakup: *Gondwana Research*, v. 39, p. 131–144, doi: 10.1016/j.gr.2016.06.012.
- Petersen, K.D., Schiffer, C., and Nagel, T.J., 2018, LIP formation and protracted lower mantle upwelling induced by rifting and delamination: *Scientific Reports*, p. 1–11, doi: 10.1038/s41598-018-34194-0.

- Phethean, J., Kalnins, L., van Hunen, J., Biffi, P.G., Davies, R.J., and McCaffrey, K.J.W., 2016, Madagascar's escape from Africa: A high-resolution plate reconstruction for the Western Somali Basin and implications for supercontinent dispersal: *Geochemistry, Geophysics, Geosystems*, v. 17, no. 7, p. 2825–2834, doi: 10.1002/2016GC006406.
- Phillips, T.B., Jackson, C.A., Bell, R.E., and Duffy, O.B., 2018, Oblique reactivation of lithosphere-scale lineaments controls rift physiography – The upper crustal expression of the Sorgenfrei-Tornquist Zone, offshore southern Norway: *Soild Earth*, v. 9, p. 403–429, doi: 10.5194/se-9-403-2018.
- Piepjohn, K., von Gosen, W., and Tessensohn, F., 2016, The Eureka deformation in the Arctic: an outline: *Journal of the Geological Society*, v. 173, p. jgs2016-081, doi: 10.1144/jgs2016-081.
- Pindell, J., and Dewey, J.F., 1982, Permo- Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: *Tectonics*, v. 1, no. 2, p. 179–211.
- Pique, A., and Laville, E., 1996, The Central Atlantic Rifting: reactivation of Plaeozoic structures: *Journal of Geodynamics*, v. 21, no. 3, p. 235–255.
- Pirajno, F., and Santosh, M., 2015, Mantle plumes, supercontinents, intracontinental rifting and mineral systems: *Precambrian Research*, v. 259, p. 243–261, doi: 10.1016/j.precamres.2014.12.016.
- Powell, C.M., Roots, S.R., and Veevers, J.J., 1988, Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean: *Tectonophysics*, v. 155, no. 1–4, p. 261–283.
- Presnall, D.C., and Gudfinnsson, G.H., 2011, Oceanic volcanism from the low-velocity zone - without mantle plumes: *Journal of Petrology*, v. 52, no. 7–8, p. 1533–1546, doi: 10.1093/petrology/egq093.
- Puffer, J.H., 2001, Contrasting high field strength element contents of continental flood basalts from plume versus reactivated-arc sources: *Geology*, v. 29, no. 8, p. 675–678.
- Quirk, D.G., Hertle, M., Jeppesen, J.W., Raven, M., Mohriak, W.U., Kann, D.J., Nørgaard, M., Howe, M.J., Hsu, D., and Coffey, B., 2013, Rifting, subsidence and continental break-up above a mantle plume in the central South Atlantic: *Geological Society, London, Special Publications*, v. 369, no. 1, p. 185–214.
- Rabinowitz, P.D., Coffin, M.F., and Falvey, D., 1983, The Separation of Madagascar and Africa: *Science*, v. 220, no. 4592, p. 67 LP-69.
- Rabinowitz, P.D., and Labrecque, J., 1979, The Mesozoic South Atlantic Ocean and Evolution of Its Continental Margins: *Journal of Geophysical Research*, v. 84, no. October 1971.
- Ragland, P.C., Hatcher, R.D., and Whittington, D., 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas: A preliminary assessment: *Geology*, v. 11, no. 7, p. 394–399.
- Reeves, C. V., 2017, The development of the East African margin during Jurassic and Lower Cretaceous times: a perspective from global tectonics: *Petroleum Geoscience*, v. 24, no.

1, p. 41–56.

Reeves, C., 2014, The position of Madagascar within Gondwana and its movements during Gondwana dispersal: *Journal of African Earth Sciences*, v. 94, p. 45–57, doi: <https://doi.org/10.1016/j.jafrearsci.2013.07.011>.

Reeves, C., Teasdale, J., and Mahanjane, E.S., 2016, Insight into the East Coast of Africa from a new tectonic model of the early Indian Ocean: Geological Society, London, Special Publications, v. 431, p. 299–322, doi: 10.1144/SP431.12.

Reeves, C. V, De Wit, M.J., and Sahu, B.K., 2004, Tight reassembly of Gondwana exposes Phanerozoic shears in Africa as global tectonic players: *Gondwana Research*, v. 7, no. 1, p. 7–19.

Renne, P.R., Ernesto, M., Pacca, I.G., Coe, R.S., Glen, J.M., Prévot, M., and Perrin, M., 1992, The Age of Paraná Flood Volcanism, Rifting of Gondwanaland, and the Jurassic-Cretaceous Boundary: *Science*, v. 258, no. 5084, p. 975 LP-979.

Reston, T.J., 2009, The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: A synthesis: *Tectonophysics*, v. 468, no. 1–4, p. 6–27, doi: 10.1016/j.tecto.2008.09.002.

Rey, P., Vanderhaeghe, O., and Teyssier, C., 2001, Gravitational collapse of the continental crust: definition, regimes and modes: *Tectonophysics*, v. 342, no. 3, p. 435–449, doi: [https://doi.org/10.1016/S0040-1951\(01\)00174-3](https://doi.org/10.1016/S0040-1951(01)00174-3).

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot-spot tracks: plume heads and tails: *Science*, v. 246, no. 4926, p. 103–107.

Richards, M.A., and Griffiths, R.W., 1988, Deflection of plumes by mantle shear flow: experimental results and a simple theory: *Geophysical Journal International*, v. 94, no. 3, p. 367–376.

Riisager, J., Riisager, P., and Pedersen, A.K., 2003, Paleomagnetism of large igneous provinces: Case-study from West Greenland, North Atlantic igneous province: *Earth and Planetary Science Letters*, v. 214, no. 3–4, p. 409–425, doi: 10.1016/S0012-821X(03)00367-4.

Riley, T.R., and Knight, K.B., 2001, Age of Pre-Break-Up Gondwana Magmatism: *Antarctic Science*, v. 13, no. 2, p. 99–110, doi: DOI: 10.1017/S0954102001000177.

Roberts, D., 2003, The Scandinavian Caledonides: Event chronology, palaeogeographic settings and likely modern analogues: *Tectonophysics*, v. 365, no. 1–4, p. 283–299, doi: 10.1016/S0040-1951(03)00026-X.

Roberts, A.M., Alvey, A.D., and Kusznir, N.J., 2018, Crustal structure and heat-flow history in the UK Rockall Basin, derived from backstripping and gravity-inversion analysis: *Petroleum Geoscience*,.

Rocha-Júnior, E.R. V, Marques, L.S., Babinski, M., Nardy, A.J.R., Figueiredo, A.M.G., and Machado, F.B., 2013, Sr-Nd-Pb isotopic constraints on the nature of the mantle sources involved in the genesis of the high-Ti tholeiites from northern Paraná Continental Flood

- Basalts (Brazil): *Journal of South American Earth Sciences*, v. 46, p. 9–25, doi: 10.1016/j.jsames.2013.04.004.
- Roeser, H.A., Steiner, C., Schreckenberger, B., and Block, M., 2002, Structural development of the Jurassic Magnetic Quiet Zone off Morocco and identification of Middle Jurassic magnetic lineations: *Journal of Geophysical Research: Solid Earth*, v. 107, no. B10, p. 2207, doi: 10.1029/2000JB000094.
- Roest, W.R., and Srivastava, S.P., 1989, Sea-floor spreading in the Labrador Sea: a new reconstruction: *Geology*, v. 17, no. 11, p. 1000–1003, doi: 10.1130/0091-7613(1989)017<1000:SFSITL>2.3.CO;2.
- Rogers, J.J.W., 1996, A History of Continents in the past Three Billion Years: *Journal of Geology*, v. 104, no. 1, p. 91–107.
- Rohde, J.K., van den Bogaard, P., Hoernle, K., Hauff, F., and Werner, R., 2013, Evidence for an age progression along the Tristan-Gough volcanic track from new $^{40}\text{Ar}/^{39}\text{Ar}$ ages on phenocryst phases: *Tectonophysics*, v. 604, p. 60–71.
- Rotevatn, A., Kristensen, T.B., Ksienzyk, A.K., Wemmer, K., Henstra, G.A., Midtkandal, I., Grundvåg, S.-A., and Andresen, A., 2018, Structural inheritance and rapid rift-length establishment in a multiphase rift: the East Greenland rift system and its Caledonian orogenic ancestry: *Tectonics*.
- Le Roy, P., and Piqué, A., 2001, Triassic–Liassic Western Moroccan synrift basins in relation to the Central Atlantic opening: *Marine Geology*, v. 172, no. 3, p. 359–381, doi: [https://doi.org/10.1016/S0025-3227\(00\)00130-4](https://doi.org/10.1016/S0025-3227(00)00130-4).
- Ryberg, T., Haberland, C., Haberland, T., Weber, M.H., Bauer, K., Behrmann, J.H., and Jokat, W., 2015, Crustal structure of northwest Namibia: Evidence for plume-rift-continent interaction: *Geology*, v. 43, no. 8, p. 739 LP-742.
- Sager, W.W., 2014, Scientific drilling in the South Atlantic: Rio Grande Rise, Walvis Ridge and surrounding areas, in *South Atlantic Workshop*, Rio de Janeiro, Brazil.
- Sahabi, M., Aslanian, D., and Olivet, J.-L., 2004, Un nouveau point de départ pour l'histoire de l'Atlantique central: *Comptes Rendus Geoscience*, v. 336, no. 12, p. 1041–1052, doi: <https://doi.org/10.1016/j.crte.2004.03.017>.
- Salman, G., and Abdula, I., 1995, Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique: *Sedimentary Geology*, v. 96, no. 1, p. 7–41, doi: [https://doi.org/10.1016/0037-0738\(95\)00125-R](https://doi.org/10.1016/0037-0738(95)00125-R).
- Salomon, E., Koehn, D., and Passchier, C., 2015, Brittle reactivation of ductile shear zones in NW Namibia in relation to South Atlantic rifting: *Tectonics*, v. 34, no. 1, p. 70–85.
- Salomon, E., Passchier, C., and Koehn, D., 2017, Asymmetric continental deformation during South Atlantic rifting along southern Brazil and Namibia: *Gondwana Research*, v. 51, p. 170–176, doi: 10.1016/j.gr.2017.08.001.
- Salters, V.J.M., Ragland, P.C., Hames, W.E., Milla, K., and Ruppel, C., 2003, Temporal Chemical Variations Within Lowermost Jurassic Tholeiitic Magmas of the Central

- Atlantic Magmatic Province, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, American Geophysical Union, p. 163–177.
- Santosh, M., Maruyama, S., and Yamamoto, S., 2009, The making and breaking of supercontinents: Some speculations based on superplumes, super downwelling and the role of tectosphere: *Gondwana Research*, v. 15, no. 3–4, p. 324–341, doi: 10.1016/j.gr.2008.11.004.
- Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., and Kent, R.W., 1997, The North Atlantic Igneous Province (J. J. honey & M. F. Coffin, Eds.): *Geophysical Monograph Series: Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*, p. 45–93, doi: 10.1029/GM100p0045.
- Saunders, A.D., Jones, S.M., Morgan, L.A., Pierce, K.L., Widdowson, M., and Xu, Y.G., 2007, Regional uplift associated with continental large igneous provinces: The roles of mantle plumes and the lithosphere: *Chemical Geology*, v. 241, no. 3–4, p. 282–318, doi: 10.1016/j.chemgeo.2007.01.017.
- Saunders, A.D., Storey, M., W., K.R., and Norry, M., 1992, Consequences of plume-lithosphere interactions: *Geological Society, London, Special Publications*, , no. 68, p. 41–60.
- Sauter, D., Ringenbach, J.C., Cannat, M., Maurin, T., Manatschal, G., and McDermott, K.G., 2018, Intraplate Deformation of Oceanic Crust in the West Somali Basin: Insights From Long- offset Reflection Seismic Data: *Tectonics*, v. 37, no. 2, p. 588–603.
- Sauter, D., Unternehr, P., Manatschal, G., Tugend, J., Cannat, M., Le Quellec, P., Kuszniir, N., Munsch, M., Leroy, S., Mercier de Lepinay, J., Granath, J.W., and Horn, B.W., 2016, Evidence for magma entrapment below oceanic crust from deep seismic reflections in the Western Somali Basin: *Geology*, v. 44, no. 6, p. 407–410.
- Schandelmeier, H., Bremer, F., and Holl, H.-G., 2004, Kinematic evolution of the Morondava rift basin of SW Madagascar—from wrench tectonics to normal extension: *Journal of African Earth Sciences*, v. 38, no. 4, p. 321–330, doi: <https://doi.org/10.1016/j.jafrearsci.2003.11.002>.
- Schettino, A., and Scotese, C.R., 2005, Apparent polar wander paths for the major continents (200 Ma to the present day): a palaeomagnetic reference frame for global plate tectonic reconstructions: *Geophysical Journal International*, v. 163, no. 2, p. 727–759.
- Schiffer, C., Doré, A.G., Foulger, G.R., Franke, D., Geoffroy, L., Gernigon, L., Holdsworth, R.E., Kuszniir, N., Lundin, E., McCaffrey, K., Peace, A., Petersen, K., Stephenson, R., Stoker, M., et al. The role of tectonic inheritance in the evolution of the North Atlantic: *Earth-Science Reviews*,.
- Schiffer, C., Peace, A.L.A., Phethean, J., Gernigon, L., McCaffrey, K.J.W., Petersen, K.D., and Foulger, G.R., 2018, The Jan Mayen Microplate Complex and the Wilson Cycle: in *Tectonic Evolution: 50 Years of the Wilson Cycle Concept*: Geological Society of London, Special Publications, v. 470, p. SP470–2, doi: 10.1144/SP470.2.
- Schiffer, C., and Stephenson, R., 2017, Regional crustal architecture of Ellesmere Island, Arctic Canada: *Geological Society of London Special Publications*,.

- Schiffer, C., Stephenson, R.A., Petersen, K.D., Nielsen, S.B., Jacobsen, B.H., Balling, N., and Macdonald, D.I.M., 2015, A sub-crustal piercing point for North Atlantic reconstructions and tectonic implications: *Geology*, v. 43, no. 12, p. 1087–1090, doi: 10.1130/G37245.1.
- Schlische, R.W., Withjack, M.O., and Olsen, P.E., 2003, Relative Timing of CAMP, Rifting, Continental Breakup, and Basin Inversion: Tectonic Significance, *in* The Central Atlantic Magmatic Province: Insights from Fragments of Pangea, American Geophysical Union, p. 33–59.
- Scotese, C.R., 2009, Late Proterozoic plate tectonics and palaeogeography: a tale of two supercontinents, Rodinia and Pannotia: Geological Society, London, Special Publications, v. 326, no. 1, p. 67–83.
- Scotese, C.R., 2016, PALEOMAP PaleoAtlas for GPlates and the PaleoData Plotter Program, PALEOMAP Project.:
- Secher, K., Heaman, L.M., Nielsen, T.F.D., Jensen, S.M., Schjøth, F., and Creaser, R.A., 2009, Timing of kimberlite, carbonatite, and ultramafic lamprophyre emplacement in the alkaline province located 64°–67° N in southern West Greenland: *Lithos*, v. 112, p. 400–406, doi: 10.1016/j.lithos.2009.04.035.
- Segoufin, J., 1978, Anomalies magnetiques mesozoïques dans le bassin de Mozambique: *CR Acad. Sci. Paris*, v. 287, no. D, p. 109–112.
- Segoufin, J., and Patriat, P., 1980, Existence d'anomalies mésozoïques dans le bassin de Somalie. Implications pour les relations Afrique-Antarctique-Madagascar: *CR Acad. Sci. Paris*, v. 291, no. B, p. 85–88.
- Sengor, A.M.C., 1996, Paleotectonics of Asia: fragments of a synthesis.: The tectonic evolution of Asia, p. 486–640.
- Şengör, A.M.C., and Natal'in, B.A., 2001, Riffs of the World: Special Paper of the Geological Society of America, v. 352, p. 389–482.
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200Ma: *Earth-Science Reviews*, v. 113, no. 3–4, p. 212–270, doi: 10.1016/j.earscirev.2012.03.002.
- Shannon, P.M., Jacob, A.W.B., Makris, J., O'Reilly, B., Hauser, F., and Vogt, U., 1994, Basin evolution in the Rockall region, North Atlantic: *First Break*, v. 12, no. 10, p. 515–522.
- Shellnutt, J.G., Dostal, J., Yeh, M.-W., Gregory Shellnutt, J., Dostal, J., and Yeh, M.-W., 2017, Mantle source heterogeneity of the Early Jurassic basalt of eastern North America: *International Journal of Earth Sciences*, , no. 0123456789, doi: 10.1007/s00531-017-1519-0.
- Silver, P.G., Behn, M.D., Kelley, K., Schmitz, M., and Savage, B., 2006, Understanding cratonic flood basalts: *Earth and Planetary Science Letters*, v. 245, no. 1–2, p. 190–201.

- Simon, K., Huismans, R.S., and Beaumont, C., 2009, Dynamical modelling of lithospheric extension and small-scale convection: Implications for magmatism during the formation of volcanic rifted margins: *Geophysical Journal International*, v. 176, no. 1, p. 327–350, doi: 10.1111/j.1365-246X.2008.03891.x.
- Simpson, E.S.W., Sclater, J.G., Parsons, B., Norton, I., and Meinke, L., 1979, Mesozoic magnetic lineations in the Mozambique Basin: *Earth and Planetary Science Letters*, v. 43, no. 2, p. 260–264.
- Skogseid, J., Planke, S., Faleide, J.I., Pedersen, T., Eldholm, O., and Neverdal, F., 2000, NE Atlantic continental rifting and volcanic margin formation: Geological Society, London, Special Publications, v. 167, no. 1, p. 295–326, doi: 10.1144/GSL.SP.2000.167.01.12.
- Sleep, N.H., 1996, Lateral flow of hot plume material ponded at sublithospheric depths: *Journal of Geophysical Research*, v. 101, no. B5, p. 28065–28063, doi: 10.1029/96JB02463.
- Sleep, N.H., Ebinger, C.J., and Kendall, J.-M., 2002, Deflection of mantle plume material by cratonic keels: Geological Society, London, Special Publications, v. 199, no. 1, p. 135–150, doi: 10.1144/GSL.SP.2002.199.01.08.
- Srivastava, S.P., 1978, Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic: *Geophysical Journal International*, v. 52, no. 2, p. 313–357, doi: 10.1111/j.1365-246X.1978.tb04235.x.
- Srivastava, S.P., and Roest, W.R., 1999, Extent of oceanic crust in the Labrador Sea: *Marine and Petroleum Geology*, v. 16, no. 1, p. 65–84, doi: 10.1016/S0264-8172(98)00041-5.
- St-Onge, M.R., Van Gool, J.A.M., Garde, A.A., Scott, D.J., Gool, J.A.M. Van, Garde, A.A., Scott, D.J., Van Gool, J.A.M., Garde, A.A., and Scott, D.J., 2009, Correlation of Archaean and Palaeoproterozoic units between northeastern Canada and western Greenland: constraining the pre-collisional upper plate accretionary history of the Trans-Hudson orogen: Geological Society, London, Special Publications, v. 318, no. 1, p. 193–235, doi: 10.1144/sp318.7.
- Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons: *Earth and Planetary Science Letters*, v. 196, no. 1, p. 17–33.
- Stampfli, G.M., Hochard, C., V  rard, C., Wilhem, C., and vonRaumer, J., 2013, The formation of Pangea: *Tectonophysics*, v. 593, p. 1–19, doi: 10.1016/j.tecto.2013.02.037.
- Stanca, R., Kearns, H., Paton, D., Hodgson, N., Rodriguez, K., and Hussein, A.A., 2016, Offshore Somalia: crustal structure and implications on thermal maturity: *First Break*, v. 34, no. December, p. 61–67.
- Stanton, N., Manatschal, G., Autin, J., Sauter, D., Maia, M., and Viana, A., 2016, Geophysical fingerprints of hyper-extended, exhumed and embryonic oceanic domains: the example from the Iberia–Newfoundland rifted margins: *Marine Geophysical Research*, v. 37, no. 3, p. 185–205, doi: 10.1007/s11001-016-9277-0.
- Steinberger, B., Bredow, E., Lebedev, S., Schaeffer, A., and Torsvik, T.H., 2018, Widespread

- volcanism in the Greenland–North Atlantic region explained by the Iceland plume: *Nature Geoscience*, doi: 10.1038/s41561-018-0251-0.
- Stephenson, R.A., Jess, S., Nielsen, S.S.S.B., Peace, A.L.A.L., and Schiffer, C., 2018, Late Cretaceous–Cenozoic intraplate basin inversion in the North Atlantic–western Alpine–Tethys realm: *Earth-Science Reviews*, v. 20, p. 3933.
- Stica, J.M., Zalán, P.V., and Ferrari, A.L., 2014, The evolution of rifting on the volcanic margin of the Pelotas Basin and the contextualization of the Paraná–Etendeka LIP in the separation of Gondwana in the South Atlantic: *Marine and Petroleum Geology*, v. 50, no. Supplement C, p. 1–21, doi: <https://doi.org/10.1016/j.marpetgeo.2013.10.015>.
- Stoker, M.S., Stewart, M.A., Shannon, P.M., Bjerager, M., and Nielsen, T., 2016, An overview of the Upper Palaeozoic – Mesozoic stratigraphy of the NE Atlantic region: The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution, v. 447, p. 11–68, doi: 10.1144/SP447.2.
- Štolfova, K., and Shannon, P.M., 2009, Permo- Triassic development from Ireland to Norway: basin architecture and regional controls: *Geological Journal*, v. 44, no. 6, p. 652–676.
- Storey, B.C., 1995, The role of mantle plumes in continental breakup: case histories from Gondwanaland: *Nature*, v. 377, no. 6547, p. 301–308, doi: 10.1038/377301a0.
- Storey, M., Duncan, R.A.R.A., and Tegner, C., 2007, Timing and duration of volcanism in the North Atlantic Igneous Province: Implications for geodynamics and links to the Iceland hotspot: *Chemical Geology*, v. 241, no. 3–4, p. 264–281, doi: 10.1016/j.chemgeo.2007.01.016.
- Storey, B.C., Leat, P.T., and Ferris, J.K., 2001, The location of mantleplume centers during the initial stages of Gondwana break-up (R. E. Ernst & K. L. Buchan, Eds.): R.E. Ernst and K.L. Buchan (Editors), *Mantle Plumes: Their identification through time*. Geological Society of America Special Papers, p. 71–80.
- Suckro, S.K.S.K., Gohl, K., Funck, T., Heyde, I., Schreckenberger, B., Gerlings, J., and Damm, V., 2013, The Davis Strait crust-a transform margin between two oceanic basins: *Geophysical Journal International*, v. 193, no. 1, p. 78–97, doi: 10.1093/gji/ggs126.
- Szatmari, P., 2000, Habitat of petroleum along the South Atlantic margins.: In: AAPG Memoir: Petroleum systems of South Atlantic margins. M.R. Mello and B.J. Katz (Editors), p. 69–75.
- Talwani, M., and Eldholm, O., 1977, Evolution of the Norwegian–Greenland Sea: *Bulletin of the Geological Society of America*, v. 88, no. 7, p. 969–999, doi: 10.1130/0016-7606(1977)88<969:EOTNS>2.0.CO;2.
- Tappe, S., Foley, S.F., Jenner, G.A., Heaman, L.M., Kjarsgaard, B.A., Romer, R.L., Stracke, A., Joyce, N., and Hoefs, J., 2006, Genesis of ultramafic lamprophyres and carbonatites at Aillik Bay, Labrador: A consequence of incipient lithospheric thinning beneath the North Atlantic Craton: *Journal of Petrology*, v. 47, no. 7, p. 1261–1315, doi: 10.1093/petrology/egl008.

- Tappe, S., Foley, S.F., Stracke, A., Romer, R.L., Kjarsgaard, B.A., Heaman, L.M., and Joyce, N., 2007, Craton reactivation on the Labrador Sea margins: $^{40}\text{Ar}/^{39}\text{Ar}$ age and Sr-Nd-Hf-Pb isotope constraints from alkaline and carbonatite intrusives: *Earth and Planetary Science Letters*, v. 256, no. 3–4, p. 433–454, doi: 10.1016/j.epsl.2007.01.036.
- Tate, M.P., 1993, Structural framework and tectono-stratigraphic evolution of the Porcupine Seabight Basin, offshore Western Ireland: *Marine and Petroleum Geology*, v. 10, no. 2, p. 95–123, doi: 10.1016/0264-8172(93)90016-L.
- Tegner, C., Brooks, C.K., Duncan, R.A., Heister, L.E., and Bernstein, S., 2008, ^{40}Ar - ^{39}Ar ages of intrusions in East Greenland: Rift-to-drift transition over the Iceland hotspot: *Lithos*, v. 101, no. 3–4, p. 480–500, doi: 10.1016/j.lithos.2007.09.001.
- Tegner, C., Duncan, R.A., Bernstein, S., Brooks, C.K., Bird, D.K., and Storey, M., 1998, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of Tertiary mafic intrusions along the East Greenland rifted margin: Relation to flood basalts and the Iceland hotspot track: *Earth and Planetary Science Letters*, v. 156, no. 1–2, p. 75–88, doi: 10.1016/S0012-821X(97)00206-9.
- Thomas, W.A., 2018, Tectonic inheritance at multiple scales during more than two complete Wilson cycles recorded in eastern North America: Geological Society of London, Special Publications: Fifty Years of the Wilson Cycle Concept in Plate Tectonics, v. 470, doi: 10.1144/SP470.4.
- Thórarinnsson, S.B., Söderlund, U., Døssing, A., Holm, P.M., Ernst, R.E., and Tegner, C., 2015, Rift magmatism on the Eurasia basin margin: U–Pb baddeleyite ages of alkaline dyke swarms in North Greenland: *Journal of the Geological Society*, v. 172, no. 6, p. 721–726, doi: 10.1144/jgs2015-049.
- Timmerman, M.J., Heeremans, M., Kirstein, L.A., Larsen, B.T., Spencer-Dunworth, E.-A., and Sundvoll, B., 2009, Linking changes in tectonic style with magmatism in northern Europe during the late Carboniferous to latest Permian: *Tectonophysics*, v. 473, no. 3–4, p. 375–390.
- Tollo, R.P., and Gottfried, D., 1989, Early Jurassic quartz normative magmatism of the Eastern North American province: Evidence for independent magmas and distinct sources: *International Association of Volcanology and Chemistry and the Earth's Interior, Continental Magmatism Abstracts*, New Mexico Bureau of Mines and Mineral Resources, v. Bulletin 1, p. 31.
- Tominaga, M., Sager, W.W., Tivey, M.A., and Lee, S., 2008, Deep- tow magnetic anomaly study of the Pacific Jurassic Quiet Zone and implications for the geomagnetic polarity reversal timescale and geomagnetic field behavior: *Journal of Geophysical Research: Solid Earth*, v. 113, no. B7.
- Tomurtogoo, O., Windley, B.F., Kröner, A., Badarch, G., and Liu, D.Y., 2005, Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol–Okhotsk ocean, suture and orogen: *Journal of the Geological Society*, v. 162, no. 1, p. 125–134.
- Torsvik, T.H., Carlos, D., Mosar, J., Cocks, L.R.M., and Malme, T.N., 2002, Global reconstructions and North Atlantic paleogeography 440 Ma to recent: *BATLAS—Mid*

- Norway plate reconstruction atlas with global and Atlantic perspectives, p. 18–39.
- Torsvik, T.H., Rouse, S., Labails, C., and Smethurst, M.A., 2009, A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin: *Geophysical Journal International*, v. 177, no. 3, p. 1315–1333.
- Torsvik, T.H., Smethurst, M.A., Meert, J.G., VanderVoo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A., and Walderhaug, H.J., 1996, Continental break-up and collision in the Neoproterozoic and Palaeozoic - A tale of Baltica and Laurentia: *Earth-Science Reviews*, v. 40, no. 3–4, p. 229–258, doi: 10.1016/0012-8252(96)00008-6.
- Trumbull, R.B., Reid, D.L., de Beer, C., van Acken, D., and Romer, R.L., 2007, Magmatism and continental breakup at the west margin of southern Africa: A geochemical comparison of dolerite dikes from northwestern Namibia and the Western Cape: *South African Journal of Geology*, v. 110, no. 2–3, p. 477 LP-502.
- Tucholke, B.E., Sawyer, D.S., and Sibuet, J.-C., 2007, Breakup of the Newfoundland Iberia rift: *Geological Society, London, Special Publications*, v. 282, no. 1, p. 9–46, doi: 10.1144/SP282.2.
- Umpleby, D.C., 1979, *Geology of the Labrador Shelf*: Geological Survey of Canada, v. 79–13.
- Upton, B.G.J., 1988, History of Tertiary igneous activity in the N Atlantic borderlands: *Geological Society, London, Special Publications*, v. 39, no. 1, p. 429–453, doi: 10.1144/GSL.SP.1988.039.01.38.
- Veevers, J.J., 2004, Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma breakup: Supercontinental tectonics via stratigraphy and radiometric dating: *Earth-Science Reviews*, v. 68, no. 1–2, p. 1–132, doi: 10.1016/j.earscirev.2004.05.002.
- Veevers, J.J., 2012, Reconstructions before rifting and drifting reveal the geological connections between Antarctica and its conjugates in Gondwanaland: *Earth-Science Reviews*, v. 111, no. 3–4, p. 249–318, doi: 10.1016/j.earscirev.2011.11.009.
- Verati, C., Rapaille, C., Féraud, G., Marzoli, A., Bertrand, H., and Youbi, N., 2007, ⁴⁰Ar/³⁹Ar ages and duration of the Central Atlantic Magmatic Province volcanism in Morocco and Portugal and its relation to the Triassic-Jurassic boundary: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 244, no. 1–4, p. 308–325, doi: 10.1016/j.palaeo.2006.06.033.
- Verwoerd, W.J., Chevallier, L., and Thomson, J.W., 1990, Oceanic Islands on the Antarctic Plate—summary: *Volcanoes of the Antarctic Plate and Southern Oceans*, Antarctic Research Series, v. 48, p. 397–404.
- Vogt, P.R., and Avery, O.E., 1974, Detailed magnetic surveys in the Northeast Atlantic and Labrador Sea: *Journal of Geophysical Research*, v. 79, no. 2, p. 363–389, doi: 10.1029/JB079i002p00363.
- Watkeys, M.K., 2002, Development of the Lebombo rifted volcanic margin of southeast Africa: *Special Paper - Geological Society of America*, v. 362, p. 27–46, doi: 10.1130/0-

8137-2362-0.27.

- Wegener, A., 1915, Die Entstehung der Kontinente und Ozeane: Sammlung Vieweg, Heft 23. Friedr. Vieweg & Sohn, Braunschweig, p. 94.
- Weigand, P.W., and Ragland, P.C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, no. 3, p. 195–214, doi: 10.1007/BF00373305.
- Welford, J.K., Peace, A.L., Geng, M., Dehler, S.A., and Dickie, K., 2018, Crustal structure of Baffin Bay from constrained three-dimensional gravity inversion and deformable plate tectonic models: Geophysical Journal International, doi: 10.1093/gji/ggy193.
- White, R.S., 1988, A hot-spot model for early Tertiary volcanism in the N Atlantic: Geological Society, London, Special Publications, v. 39, no. 1, p. 3–13, doi: 10.1144/GSL.SP.1988.039.01.02.
- White, R.S., 1992, Magmatism during and after continental break-up: Geological Society, London, Special Publications, v. 68, no. 1, p. 1–16, doi: 10.1144/GSL.SP.1992.068.01.01.
- White, N., Thompson, M., and Barwise, T., 2003, Understanding the thermal evolution of deep-water continental margins.: Nature, v. 426, no. 6964, p. 334–343, doi: 10.1038/nature02133.
- Whitmarsh, R.B., Manatschal, G., and Minshull, T. a, 2001, Evolution of magma-poor continental margins from rifting to seafloor spreading.: Nature, v. 413, no. 6852, p. 150–154, doi: 10.1038/35093085.
- Wilkinson, C.M., Ganerød, M., Hendriks, B.W.H., and Eide, E.A., 2016, Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP): Geological Society Special Publications,.
- Will, T.M., Frimmel, H.E., and Pfänder, J.A., 2016, Möwe Bay Dykes, Northwestern Namibia: Geochemical and geochronological evidence for different mantle source regions during the Cretaceous opening of the South Atlantic: Chemical Geology, v. 444, no. Supplement C, p. 141–157, doi: <https://doi.org/10.1016/j.chemgeo.2016.08.040>.
- Williams, C.A., 1975, Sea-floor spreading in the Bay of Biscay and its relationship to the North Atlantic: Earth and Planetary Science Letters, v. 24, no. 3, p. 440–456, doi: [https://doi.org/10.1016/0012-821X\(75\)90151-X](https://doi.org/10.1016/0012-821X(75)90151-X).
- Williams, S.E., Whittaker, J.M., Halpin, J.A., and Müller, R.D., 2019, Australian-Antarctic break up and seafloor spreading: Balancing geological and geophysical constraints: Earth-Science Reviews, v. 188, p. 41–58, doi: 10.1016/J.EARSCIREV.2018.10.011.
- Wilson, J.T., 1966, Did the Atlantic close and the re-open? Nature, v. 209, no. 5050, p. 1246–1248, doi: 10.1038/211676a0.
- Wilson, M., 1997, Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume: Journal of the Geological Society, v. 154, no. 3, p. 491–495, doi: 10.1144/gsjgs.154.3.0491.

- Wilson, R.W., Klint, K.E.S., van Gool, J.A.M., McCaffrey, K.J.W., Holdsworth, R.E., and Chalmers, J.A., 2006, Faults and fractures in central West Greenland: onshore expression of continental break-up and sea-floor spreading in the Labrador–Baffin Bay Sea: Geological Survey Of Denmark And Greenland Bulletin, v. 11, p. 185–204.
- Wilton, D., Burden, E., and Greening, A., 2016, The Ford's Bight Diatreme A Cretaceous Alnöite Pipe from the Northern Labrador Coast and Possible Onland Remnant from the Opening of the Labrador Sea: Arctic Technology Conference, p. 1–10.
- Wilton, D.H.C., Taylor, R.C., Sylvester, P.J., and Penney, G.T., 2002, A Review of Kimberlitic and Ultramafic Lamprophyre Intrusives From Northern Labrador: Current Research, v. 02-1, p. 343–352.
- Withjack, M.O., Schlische, R.W., and Olsen, P.E., 2012, Development of the passive margin of eastern North America: Mesozoic rifting, igneous activity, and breakup, *in* Regional Geology and Tectonics: Phanerozoic Rift Systems and Sedimentary Basins, Elsevier, p. 300–335.
- Withjack, M.O., Schlische, R.W., and Olsen, P.E., 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America; an analog for other passive margins: AAPG Bulletin, v. 82, no. 5A, p. 817–835.
- Wu, L., Trudgill, B.D., and Kluth, C.F., 2016, Salt diapir reactivation and normal faulting in an oblique extensional system, Vulcan Sub-basin, NW Australia: Journal of the Geological Society, v. 173, p. jgs2016-008, doi: 10.1144/jgs2016-008.
- Yeh, M.-W., and Shellnutt, J.G., 2016, The initial break-up of Pangaea elicited by Late Palaeozoic deglaciation: Scientific Reports, v. 6, no. 1, p. 31442, doi: 10.1038/srep31442.
- Zastrozhnov, D., Gernigon, L., Gogin, I., Abdelmalak, M.M., Planke, S., Faleide, J.I., Eide, S., and Myklebust, R., 2018, Cretaceous-Paleocene Evolution and Crustal Structure of the Northern Vøring Margin (Offshore Mid-Norway): Results from Integrated Geological and Geophysical Study: Tectonics, v. 37, no. 2, p. 497–528.
- Zorin, Y.A., 1999, Geodynamics of the western part of the Mongolia–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia: Tectonophysics, v. 306, no. 1, p. 33–56.

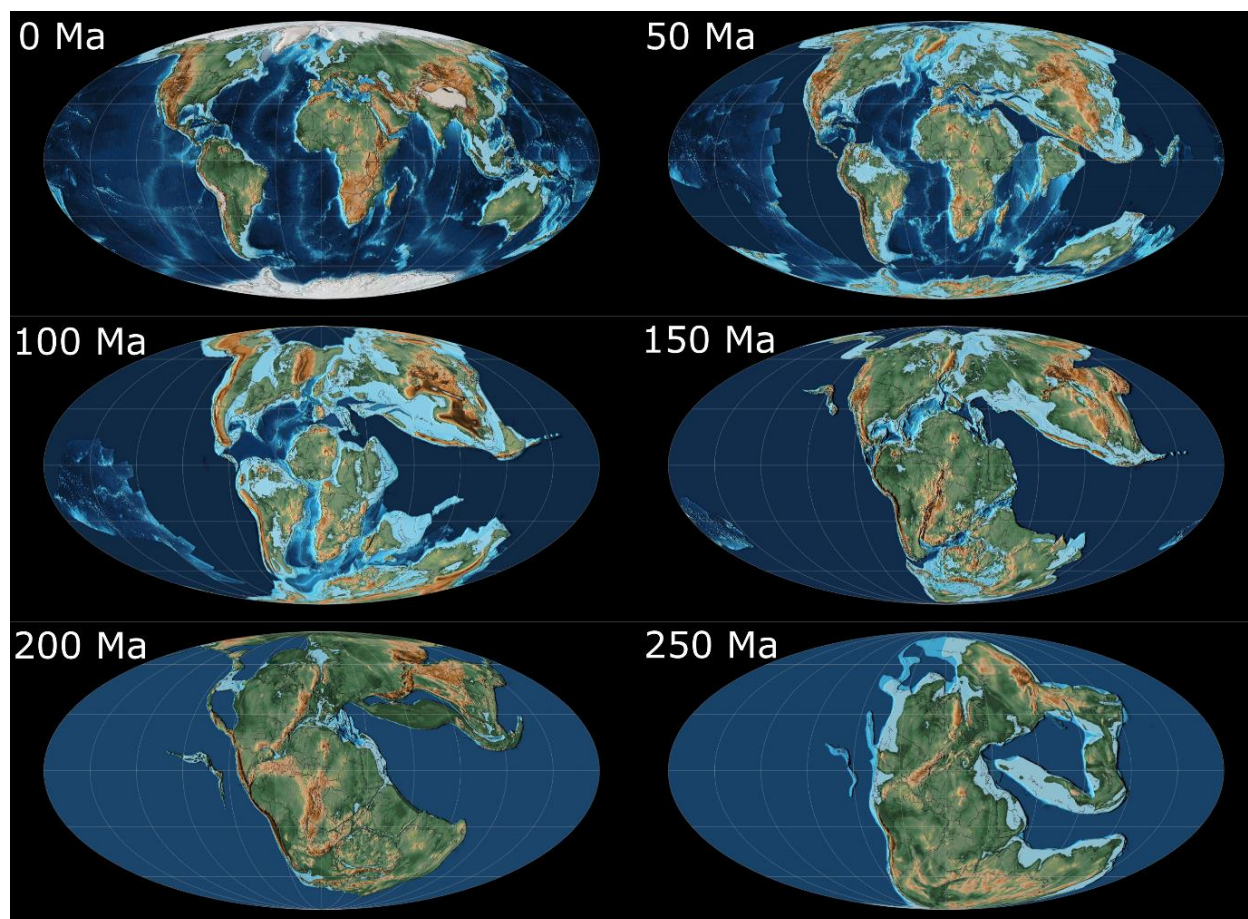


Figure 1. An overview of the disintegration of Pangaea (e.g., Frizon De Lamotte et al., 2015) using the palaeogeographic reconstruction compiled into the PALEOMAP PaleoAtlas for GPlates (Scotese, 2016) plotted using a Mollweide projection and shown at 0, 50, 100, 150, 200 and 250 Ma.

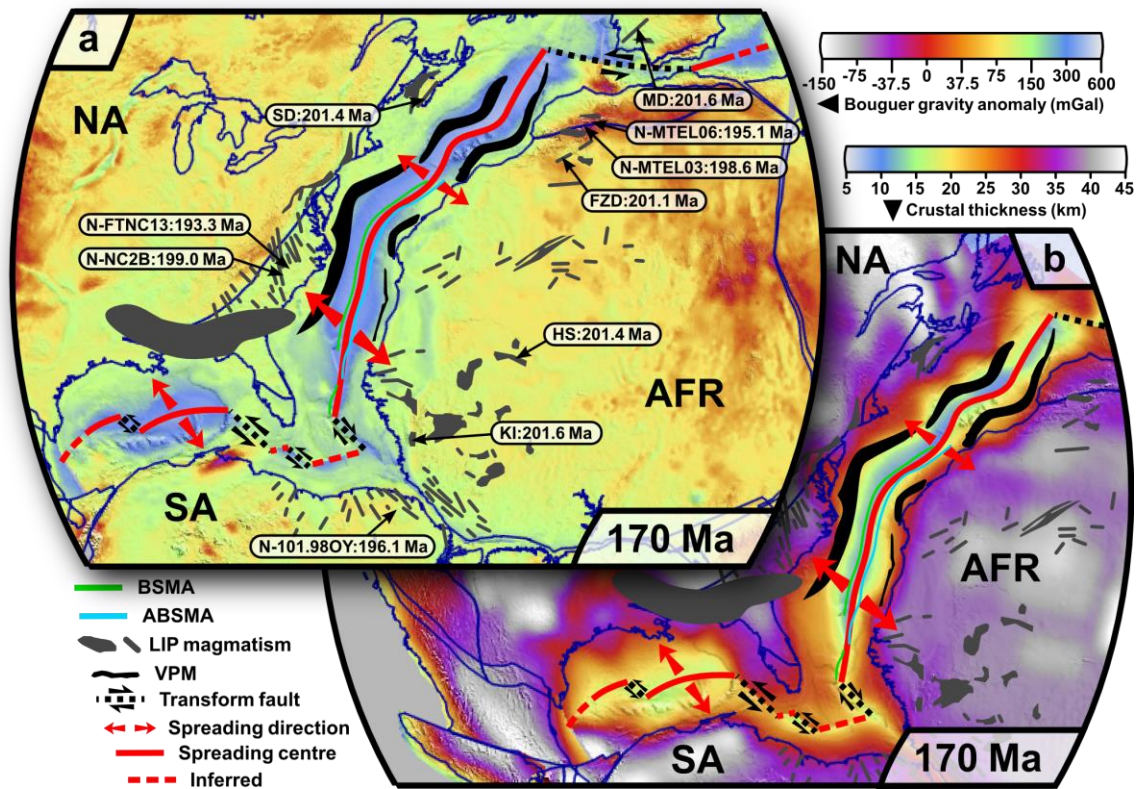


Figure 2. Breakup of the Central Atlantic shown at 170 Ma. a) Reconstructed present day Bouguer gravity anomaly (world gravity map; Balmino et al., 2012). b) Reconstructed present day crustal thickness according to the CRUST1.0 model (Laske et al., 2013). Representative LIP magmatism, SDRs, and earliest oceanic magnetic anomalies are shown with associated ages where available. NA = North America, SA = South America, AFR = Africa.

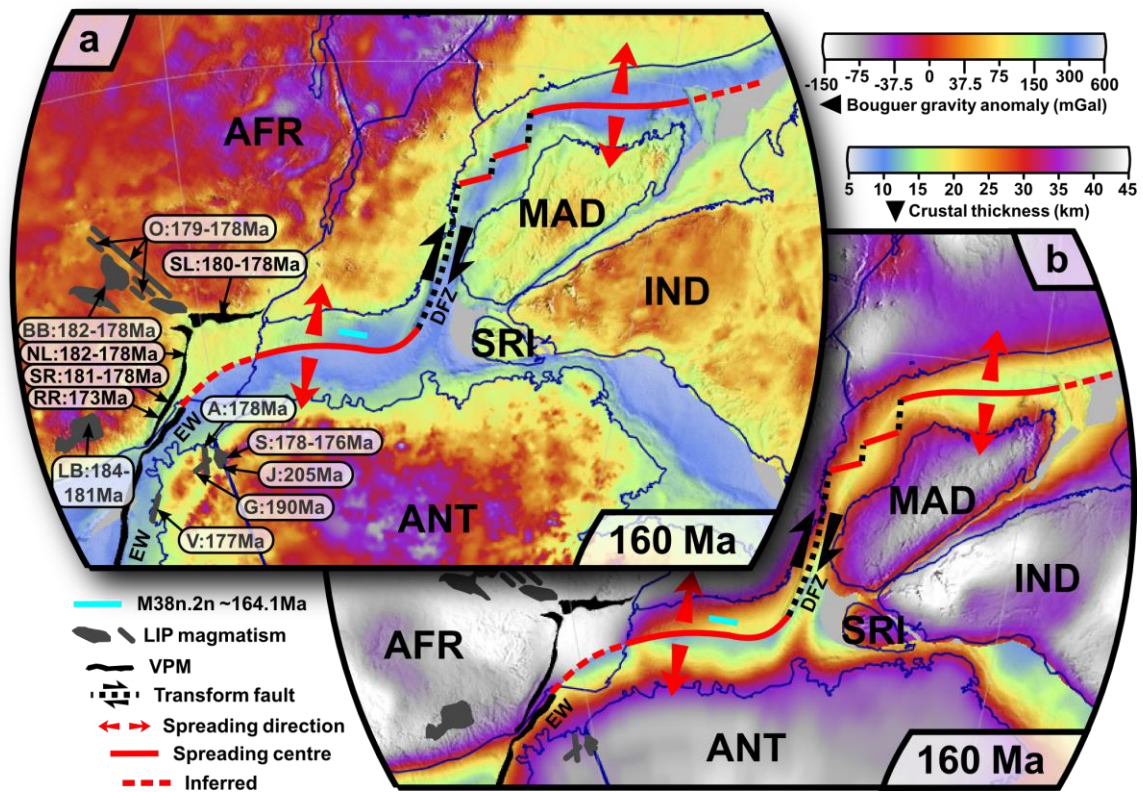


Figure 3. Breakup of East and West Gondwana shown at 160 Ma. a) Reconstructed present day Bouguer gravity anomaly (world gravity map; Balmino et al., 2012). b) Reconstructed present day crustal thickness according to the CRUST1.0 model (Laske et al., 2013). Representative LIP magmatism, SDRs, and earliest oceanic magnetic anomalies are shown with associated ages where available (Phethean et al., 2016; Klimke and Franke, 2016; Sauter et al., 2018). AFR = Africa, MAD = Madagascar, DFZ = Davie Fracture Zone; IND = India, SRI = Sri Lanka, ANT = Antarctica, and EW = Explora Wedge.

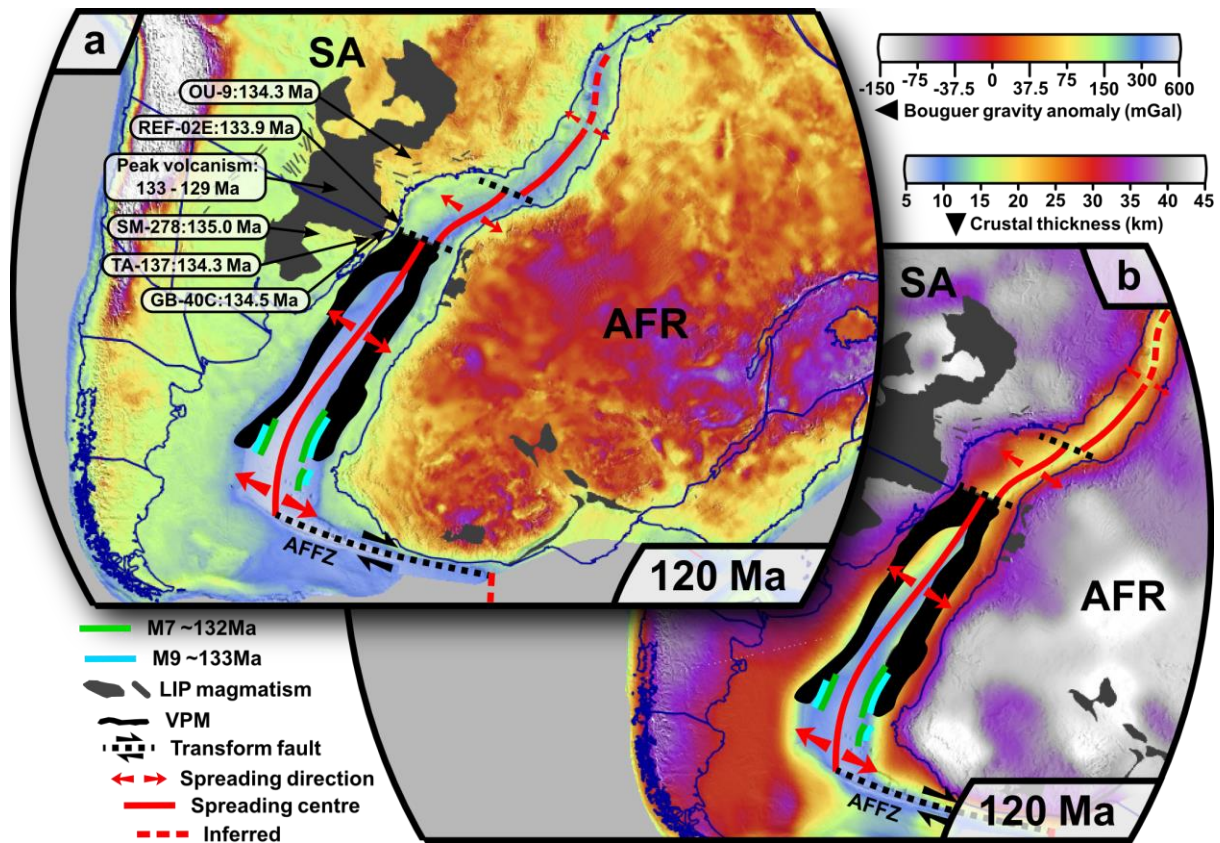


Figure 4. Breakup of the Southern Atlantic shown at 120 Ma. a) Reconstructed present day Bouguer gravity anomaly (world gravity map; Balmino et al., 2012). b) Reconstructed present day crustal thickness according to the CRUST1.0 model (Laske et al., 2013). Representative LIP magmatism, SDRs, and earliest oceanic magnetic anomalies are shown with associated ages where available (Koopmann et al., 2016). AFR = Africa, SA = South America, & AFFZ = Agulhas-Falkland Fracture Zone.

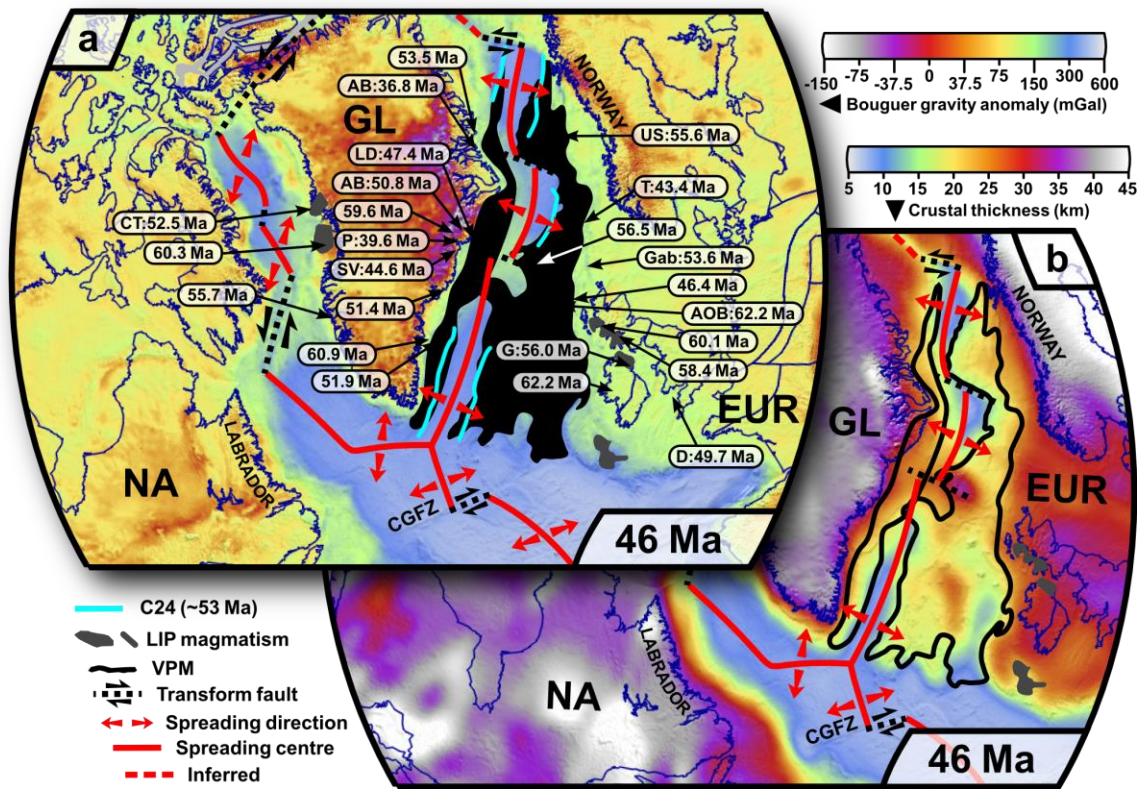


Figure 5. Breakup of the North Atlantic shown at 46 Ma. a) Reconstructed present day Bouguer gravity anomaly (world gravity map; Balmino et al., 2012). b) Reconstructed present day crustal thickness according to the CRUST1.0 model (Laske et al., 2013). LIP magmatism, SDRs, and earliest oceanic magnetic anomalies are shown with associated ages where available. Representative magmatism ages are primarily modified from the compilation made for the NAGTEC project (Wilkinson et al., 2016). Location names: AB = Alkaline Basalt; US: NA = North America, GL = Greenland, EUR = Europe, and CGFZ = Charlie-Gibbs Fracture Zone.

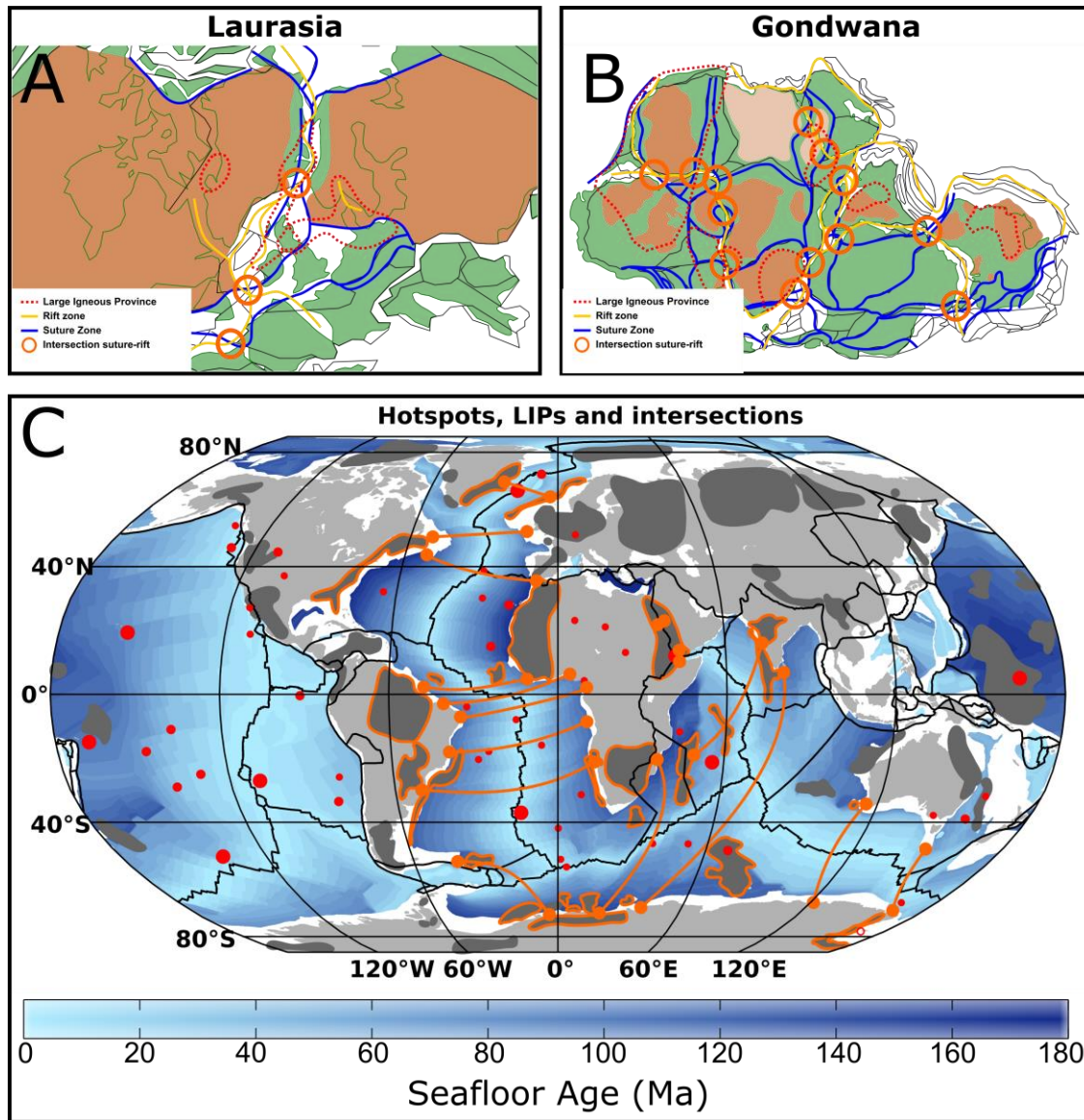


Fig. 6. Schematic reconstructions of A) Laurasia (Cocks and Torsvik, 2011) and B) Gondwana (Stampfli et al., 2013) where: green = present-day land areas; brown = cratons; blue lines = suture zones; yellow = incipient breakup axes; orange circles = intersection of breakup axes with suture zones and red dotted lines = schematic outline of LIPs. C) A global overview of the relationship between continental crust (white=offshore; pale grey = onshore), LIPs (dark grey), proposed hotspots (red dots) and the reconstructed pre-rift intersection points between suture zones and continental breakup (orange dots). Orange borders on LIPs indicate those that may have been involved with Pangaeian dispersal. The size of the red dots (representing hotspots) is related to their depths proposed by Courtillot et al. (2003) such that large dots = core-mantle boundary; medium dots = the base of the upper mantle; and small dots = the lithosphere. The orange lines show the interpolation between conjugate intersection points, and the age of oceanic crust is shown in blue. This figure illustrates the relationship between breakup-suture intersections and many LIPs that formed between the conjugate margins where intersection points existed. LIPs on this figure are taken from Ernst (2014). Seafloor age is from Seton et al. (2012).